

N A S A TECHNOLOGY PLAN

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National Aeronautics and
Space Administration

N A S A TECHNOLOGY PLAN

NASA
is an investment in
America's future. As explorers,
pioneers, and innovators, we boldly
expand frontiers in air and space
to inspire and serve America,
and to benefit the quality
of life on Earth.



National Aeronautics and
Space Administration



1.0 Introduction

The NASA Administrator, Daniel S. Goldin, describes NASA as an investment in the Nation's future. In a similar manner, this NASA Technology Plan describes an investment in NASA's future. The NASA Strategic Plan¹ describes an ambitious, exciting vision for the Agency across all its Strategic Enterprises that addresses a series of fundamental questions of science and research. This vision is so challenging that it literally depends on the success of an aggressive, cutting-edge advanced technology development program.

1.1 Objective and Purpose

The objective of this plan is to describe the NASA-wide technology program in a manner that provides not only the content of ongoing and planned activities, but also the rationale and justification for these activities in the context of NASA's future needs. The scope of this plan is Agencywide, and it includes technology investments to support all major space and aeronautics program areas, but particular emphasis is placed on longer term strategic technology efforts that will have broad impact across the spectrum of NASA activities and perhaps beyond.

Our goal is to broaden the understanding of NASA technology programs and to encourage greater participation from outside the Agency. By relating technology goals to anticipated mission needs, we hope to stimulate additional innovative approaches to technology challenges and promote more cooperative programs with partners outside NASA who share common goals. We also believe that this will increase the transfer of NASA-sponsored technology into nonaerospace applications, resulting in an even greater return on the investment in NASA.

¹ NASA Strategic Plan, 1998, NASA Policy Directive (NPD)-1000.1.

The NASA Technology Plan is targeted at three sectors of the technology community: participants, users, and investors. The participants are individuals in Government, industry, and academic institutions who are involved in managing or conducting technology activities, or may be in the future. The user communities are the mission, program, and project managers throughout the aerospace industry involved with the selection and utilization of technology in specific applications. The investors are individuals who manage or influence the funding for technology in Government, industry, or universities.

Within the context of this NASA Technology Plan, "technology" is defined as the practical application of knowledge to create the capability to do something entirely new or in an entirely new way. This can be contrasted to "scientific research," which encompasses the discovery of new knowledge from which new technology is derived, and "engineering," which uses technology derived from this knowledge to solve specific technical problems. When investments are made in a particular technology, it begins to mature—a process of testing and analysis that progressively reduces the programmatic risk of selecting that technology for an application and increases the readiness of that technology for use in a mission. Technology may be described in terms of maturity within a scale of Technology Readiness Level (TRL), shown in Appendix B, that reflects the extent to which the technology has been proven in a realistic situation. Technology funding described in this document is associated with technology development and demonstration to TRL 6 or, in some cases, TRL 7 (where the space environment is required to fully demonstrate the technology readiness). The Strategic Enterprise Technology Plans will also identify approaches to transition or insert technology into missions as they mature.

1.2 Role of Technology at NASA

Recently, NASA has undertaken sweeping changes in technology program management to strengthen and highlight the significance of advanced technology in NASA's future. These changes influence how NASA identifies new technology investments, how NASA defines new mission opportunities, and how NASA ensures the efficient transition of new technologies into missions. Overall, the adjustments have resulted in a close alignment of technology investments with the goals that are identified in the NASA Strategic Plan.

Perhaps the most significant change is a new approach to defining space missions within NASA. In the past, NASA missions were selected based on the desirability of scientific objectives and opportunities, but often with insufficient understanding of technology risks and alternative mission concepts. If required technology developments encountered problems, this approach frequently led to schedule slips and cost overruns.

As budget pressures have increased, the need for a different approach to managing technology risk in potential missions has been recognized. Instead of "technology driven by missions," a new paradigm has emerged wherein technology investments for generic classes of very challenging missions are made in advance, and specific missions are not approved for development until the enabling technologies have matured; this is referred to as "missions enabled by technologies." By reducing the schedule and cost uncertainty associated with advanced technologies, the benefits of advanced technologies can be achieved as well as significant reductions in development times.



December 28, 1998

TO: Distribution

FROM: AF/Deputy Chief Technologist, Office of the Chief Technologist

SUBJECT: NASA Technology Plan Distribution

The NASA Administrator, Daniel Goldin, describes NASA as an investment in America's future. In a similar manner, NASA technology is an investment in NASA's future. NASA has developed a Strategic Plan that describes an ambitious, exciting vision for the Agency across all its enterprises that addresses a series of fundamental questions of science and research. The enclosed document, *NASA Technology Plan*, describes this vision, and the resulting investment in technology.

The objective of the *NASA Technology Plan* is to describe the NASA technology program in a manner that provides not only the content of ongoing and planned activities, but also the rationale and justification for these activities in the context of NASA's future needs. Our goal is to broaden the understanding of NASA technology programs and to encourage greater participation from outside the Agency. By relating technology goals to anticipated mission needs, we hope to stimulate additional innovative approaches to technology challenges and promote more cooperative programs with partners outside NASA who share common goals. We also believe that this will increase the transfer of NASA-sponsored technology into non-aerospace applications, resulting in even greater return on the investment in NASA.

NASA's Office of the Chief Technologist is responsible for this plan. The printed version of the plan will be widely distributed. In addition, a website has been developed for the plan and it can be viewed at the following URL:

<http://act.uva-www.larc.nasa.gov/techplan/>

Updates to the document will be made on this website as changes are made to NASA's technology program. An option is being prepared for the website that will enable you to print future updates in a format that is consistent with the attachment. If you wish to receive electronic notification when updates are posted to the website, please complete the request form that is provided on the website. You will be able to exchange these updates with the printed version in the binder.

NASA believes this document will be useful to the entire technology community (participants, users, and investors). If you have any comments or suggestions on how to improve the plan, please address them to the NASA Office of the Chief Technologist. These comments and suggestions should be made through the "Comments Option" at the screen bottom of <http://www.hq.nasa.gov/office/codea/codeaf/>. The comments will be collected and considered in future updates to the *NASA Technology Plan*.


Gregory M. Reck

Enclosure



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Another major change in the technology program at NASA is a restructuring that moved technology management responsibility from a central organization into the four principal product organizations (the four Strategic Enterprises are described later in Section 2). This change addressed the concern that technology objectives were not sufficiently responsive to mission needs and provided for a closer integration of science and technology activities. Technology goals are now more closely linked to scientific questions and challenges, and transition plans have been established to ensure the rapid insertion of mature technologies into mission opportunities. One additional feature of this change is that the space transportation technology activities are now joined in the same organization with the aeronautics research and technology, providing for better coordination of common technology needs and projects.

Aeronautical research and technology in NASA is in a different context than space technology efforts. NASA conducts an extensive operational program in space, but it does not build or operate fleets of aircraft. The role of NASA's aeronautics research and technology development is to support national priorities in public safety, the environment, and economic development. The NASA aeronautics program enjoys a rich heritage of more than 80 years of productive Government-industry efforts that have provided a foundation for U.S. leadership in civil aviation. Aeronautics works in close alliance with its customers, including U.S. industry, the university community, the Department of Defense, and the Federal Aviation Administration, to ensure that national investments in aeronautics technology are effectively defined and coordinated and that NASA's technology products add value, are timely, and have been developed to the level at which the customer can confidently make decisions regarding the application of those technologies.

1.3 Mission and System Analysis

NASA's new approach to technology, "missions enabled by technologies," hinges on a capability to continually and rapidly explore the effects of new technology and advanced concepts on potential missions, both to guide investments in advanced technologies and to determine when critical technologies have matured to the point where a desired mission can be undertaken with acceptable programmatic risk. The framework for these studies must enable a broad spectrum of advanced technologies to be explored and must include consideration of the full life cycle of the proposed mission from conceptual design through development, validation, operation, and disposal.

The systems analysis capabilities at the NASA mission centers are being expanded and improved to meet these new demands. In a program called the Collaborative Engineering Environment, the best analytical tools for engineering and design are being incorporated into concurrent engineering environments, and communications networks are being established to ensure that advanced technology specialists from NASA, industry, and academia participate in these analytical endeavors. In addition to evolutionary improvements, a strategy has been defined for a long-term investment that will revolutionize our approach to engineering design and development. This strategy for an intelligent synthesis environment is described in Section 4.6 of this plan.

Also, programs are in place to seek and examine a wide range of new, innovative advanced concepts that address the aggressive goals set forth in the NASA Strategic Plan. Resources have been

identified to support advanced concept studies in each of the major NASA program areas, and the NASA Institute for Advanced Aerospace Concepts has been established to solicit and support advanced concept studies external to NASA. This institute will provide an independent, open forum for the analysis and definition of advanced space and aeronautics concepts. It will focus on revolutionary concepts—in particular, systems and architectures that can have a major impact on future NASA missions. More information can be found at the referenced web site (see Appendix D).

As suggested earlier, this NASA Technology Plan should contribute to a better understanding of NASA's broad challenges and the approaches inherent in the technologies that we are supporting. An improved understanding may lead to new and better concepts and approaches for meeting these challenges from both inside and outside the Agency.

1.4 NASA Investment Strategy

The technology advances needed to support future NASA missions are daunting, but in many cases, industry and other Government agencies share the same technology challenges. By communicating the objectives and goals of future NASA missions, we hope to identify areas where capabilities may already exist or where common interests could lead to collaborative efforts.

Our investment strategy within the commercial arena provides three approaches to addressing NASA technology needs. The first is associated with areas where NASA can take advantage of services (including technology and investments) provided by commercial industry. Consistent with the National Space Policy, NASA must acquire systems and services from industry when those services are commercially available, such as commercial launch services. However, there are likely other areas where a close examination or redefinition of NASA needs in light of commercial capabilities could lead to a broader use of commercial services. Two examples include a potentially greater use of commercial communications systems to meet mission operations needs and the use of commercial remote-sensing systems to acquire scientific data. The use of commercial systems can spread infrastructure costs over a wider customer base, resulting in reduced costs to NASA.

In the second type of activity, the commercial demand for products or services may not exist or be sufficiently mature to support independent industry investments at this point. However, NASA may identify opportunities for partnerships and joint investments with industry that could lead to future growth. For example, industry may be willing to share in the development of improved core space systems and related technologies if NASA identifies standards and interfaces that enable broader mission applications. Also, some future missions will rely on technology advances in non-aerospace industry sectors, such as semiconductors and graphic display systems. Here, NASA hopes to capitalize on industry investments and establish partnerships with industry to explore advances related to aerospace applications. NASA is exploring approaches to improving communications with industry and more active participation in interactions related to corporate independent research and development programs.

Finally, in the third type of activity, technology demands are unique to NASA mission needs; therefore NASA must invest in technology development and advanced concepts to enable future

generation space missions. These technology activities are accomplished by supporting technology development within industry, academia, and NASA through competitively selected contracts and grants, unsolicited contracts or grants, and inhouse efforts. Traditionally, these investments have provided a rich source of new technologies with many commercial applications, and NASA will continue a proactive program to identify and exploit these opportunities. Details of NASA activities in technology transfer and commercialization are described in Section 10.

Another key element of NASA's overall technology strategy is to work cooperatively and in partnership with other Government agencies. NASA's strategy for this technology coordination and review with other Government agencies is more fully described in Section 2.5. These shared programs with other Government agencies and industries that invest in similar efforts are the only way that NASA can meet anticipated technology needs within realistic resource expectations.

The NASA approach to investment decisions can be paraphrased as "buy when feasible, build when necessary." This investment approach is intended to build partnerships with industry and other Government agencies and promote advanced research with academia that will provide technologies for the future at lower cost, as well as to support national economic interests.

An important consideration in managing the NASA technology investment is the human resource and facility infrastructure support that is directed toward inhouse capabilities. As the investment strategy suggests, NASA will use commercial services and vigorously support industry partnerships wherever possible. However, NASA will also provide sufficient internal investments to sustain the necessary expertise to provide leadership in areas that are strategically critical to the future of the Agency. NASA does not compete with commercial spacecraft manufacturers, but the Agency will build "first-of-a-kind" spacecraft (with industry team members to ensure technology transfer) that demonstrate significantly advanced technologies or concepts.

Another component of the NASA investment strategy is the Small Business Innovative Research (SBIR) program, initiated in 1983 by Public Law 97-219. The objectives of the SBIR program are to stimulate technological innovation in the U.S. private sector, to strengthen the role of small business (including firms owned by minority or disadvantaged persons) in accomplishing Federal research and technology (R&T) goals, and to enhance commercial applications of federally supported R&T products. The SBIR program is described in more detail in Section 10. More information on related NASA programs can be obtained through the Office of Small and Disadvantaged Business Utilization at NASA Headquarters.

While a key goal of NASA's technology development program is to develop new technology that will foster new U.S. commercial space enterprises, products, services, and markets and promote secondary "spinoff" applications of NASA-developed technology to domestic industry, foreign participation in NASA's technology development programs can be considered on a case-by-case basis. As a result of the increasing trend toward globalization and the growing requirement for U.S. firms to compete in the international marketplace to maintain a competitive edge, foreign participation may be permitted on a case-by-case basis. In reviewing such opportunities, there are a number of factors that need to be weighed. These include the capability of a U.S. entity to provide the same technology as a proposed foreign participant, the impact on U.S. competitiveness, the scope of the foreign participation, and technology transfer control plans. Proposed

foreign participation in NASA's technology development plans will require the review of the Office of Chief Technologist, the supporting Enterprise Office, the Office of External Relations, and the General Counsel. Proposals for such participation should include a justification for this participation that outlines the impact on U.S. commercial competitiveness, the benefits to NASA, and the technology transfer control plan.



2.0 NASA Technology Program

2.1 NASA Strategic Plan

The NASA Strategic Plan defines the Agency's vision, mission, and fundamental questions of science and research that provide the rationale for the Agency and why it exists. The NASA vision is presented inside the cover of this plan; the three-part mission is as follows:

1. To advance and communicate scientific knowledge and understanding of the Earth, the solar system, and the universe and use the environment of space for research
2. To explore, use, and enable the development of space for human enterprise
3. To research, develop, verify, and transfer advanced aeronautics, space, and related technologies

The six fundamental questions of science and research are listed in Table 2.1-1.

The Strategic Plan identifies the following four Strategic Enterprises that are responsible for implementing the mission and answering the fundamental questions:

- Space Science
- Earth Science (formerly Mission to Planet Earth)
- Human Exploration and Development of Space
- Aero-Space Technology (formerly Aeronautics and Space Transportation Technology)

TABLE 2.1-1. FUNDAMENTAL QUESTIONS OF SCIENCE AND TECHNOLOGY

1. *How did the universe, galaxies, stars, and planets form and evolve? How can our exploration of the universe and our solar system revolutionize our understanding of physics, chemistry, and biology?*
2. *Does life in any form, however simple or complex, carbon-based or other, exist elsewhere than on planet Earth? Are there Earth-like planets beyond our solar system?*
3. *How can we utilize the knowledge of the Sun, Earth, and other planetary bodies to develop predictive environmental, climate, natural disaster, and natural resource models to help ensure sustainable development and improve the quality of life on Earth?*
4. *What is the fundamental role of gravity and cosmic radiation in vital biological, physical, and chemical systems in space, on other planetary bodies, and on Earth, and how do we apply this fundamental knowledge to the establishment of permanent human presence in space to improve life on Earth?*
5. *How can we enable revolutionary technological advances to provide air and space travel for anyone, anytime, anywhere more safely, more affordably, and with less impact on the environment and improve business opportunities and global security?*
6. *What cutting-edge technologies, processes, and techniques and engineering capabilities must we develop to enable our research agenda in the most productive, economical, and timely manner? How can we most effectively transfer the knowledge we gain from our research and discoveries to commercial ventures in the air, in space, and on Earth?*

The Strategic Plan also includes a Strategic Management System Roadmap that displays the Agency's goals in three timeframes spanning a 25-year period. The Roadmap defines unifying themes for each timeframe that characterize the primary focus of activity for that timeframe. The Roadmap lists the fundamental questions and their relationship to each of the Strategic Enterprises. This Roadmap is included for reference in Appendix C.

In response to the NASA Strategic Plan, each Enterprise has prepared an Enterprise Strategic Plan² that describes in detail the specific programs that the Enterprise will use to meet the challenges of the NASA missions. Each Enterprise has also created a specific version of the NASA Roadmap focused on its Enterprise goals, and these are included in Appendix C. These plans provide the framework for the Enterprise summaries included later in this plan.

2.2 NASA Organizational Responsibilities for Technology

The overall organizational and management structure of NASA is built around the Strategic Enterprises and is illustrated in Figure 2.2-1. Program formulation and funding responsibility for

² Space Science Enterprise Strategic Plan, NASA HQ, Nov. 17; Earth Science Strategic Enterprise Plan, 1996-2002, NASA HQ, Mar. 1997; Human Exploration and Development of Space Enterprise: The Strategic Plan, NASA HQ, Jan. 1996; Aero-Space Technology Strategic Plan: Three Pillars for Success, 1995-2000, NASA HQ, Feb. 1999.

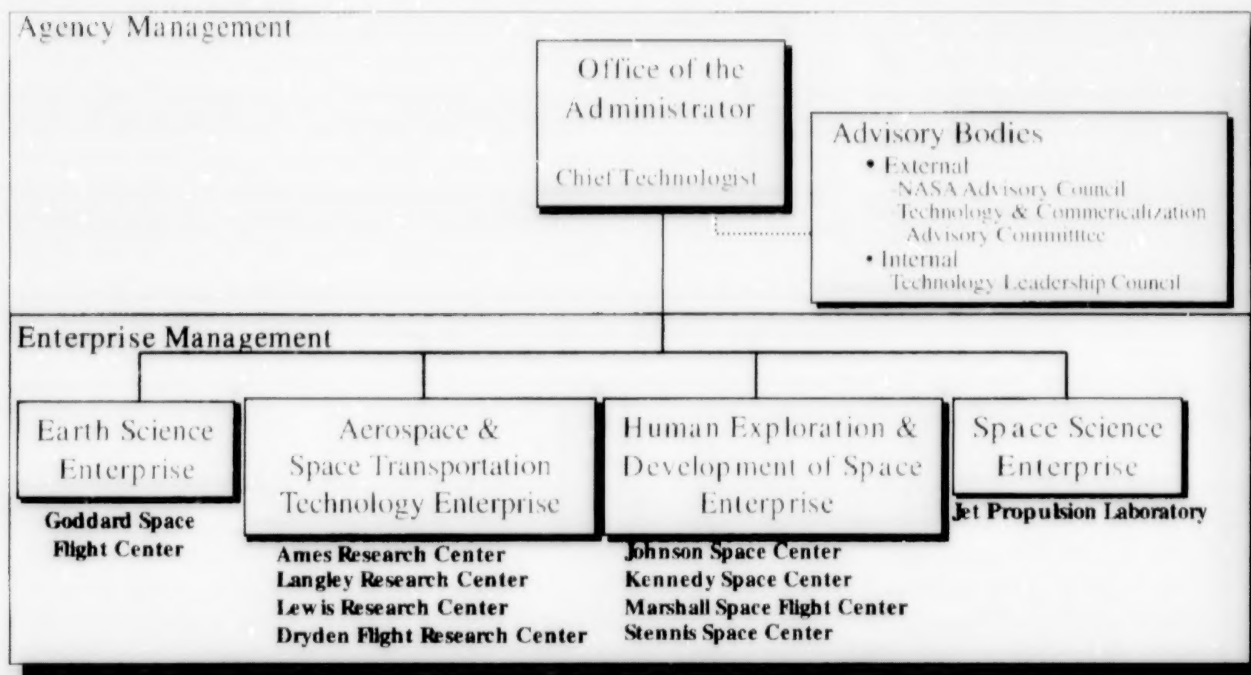


FIGURE 2.2-1. NASA TECHNOLOGY MANAGEMENT STRUCTURE

all technology activities rests with the Enterprise organizations. This ensures that technology considerations are closely coupled with mission decisions, that technologies are relevant to Enterprise needs, and that mechanisms are provided to transfer successful maturing technologies into operational systems.

The NASA Field Centers report institutionally to the Strategic Enterprises, as shown in Figure 2.2-1. However, the NASA Strategic Management Handbook (see Appendix D) designates specific "Mission Areas" and "Centers of Excellence" (see Table 2.2-1) for each of the NASA Field Centers that guide Center roles and responsibilities for technology. Thus, each Center typically supports multiple Enterprises. The NASA Field Centers participate with the Strategic Enterprises in the program formulation process, and when the technology programs have been formulated and approved, responsibility for program management and implementation is delegated to the Field Centers. The Program/Project Management Process is more fully documented in NASA Handbook 7120.³

The Office of the Chief Technologist (OCT) is located within the Office of the NASA Administrator to address issues associated with the overall technology program across the Agency. The Chief Technologist advises the Administrator and other senior officials on matters relating to technology, assures an Agencywide investment strategy for advanced innovative technology, and is the principal Agency advocate for advanced technology. The Chief Technologist also chairs the Technology Leadership Council (TLC), which includes the Associate Administrators for the Strategic Enterprise offices, the NASA Field Center Directors, the NASA Comptroller, and other senior NASA officials. This council establishes the technology strategy for the Agency, addresses critical issues, and is responsible for formulating and advancing NASA's vision for technology.

³ NASA Program and Project Management Process and Requirements, NPG 7120.5A, Office of Chief Engineer, NASA HQ, Effective Date: April 3, 1998.

TABLE 2.2-1. DESIGNATED CENTER OF EXCELLENCE AND MISSION AREAS

<i>Center</i>	<i>Designated Center of Excellence Area</i>	<i>Mission Area</i>
Ames Research Center	Information Technology	Aviation Operations Systems and Astrobiology
Dryden Flight Research Center	Atmospheric Flight Operations	Flight Research
Goddard Space Flight Center	Scientific Research	Earth Science Physics and Astronomy
Jet Propulsion Laboratory	Deep Space Systems	Planetary Science and Exploration
Johnson Space Center	Human Operations in Space	Human Exploration and Astro Materials
Kennedy Space Center	Launch and Payload Processing Systems	Space Launch
Langley Research Center	Structures and Materials	Airframe Systems and Atmospheric Science
Lewis Research Center	Turbomachinery	Aeropropulsion
Marshall Space Flight Center	Space Propulsion	Transportation Systems Development and Microgravity Research
NASA Headquarters	Agency Management	—
Stennis Space Center	Rocket Propulsion Test	Propulsion Testing

OCT works with Enterprises and the Field Centers to define the Strategic Technology Areas that are critical to the Agency's long-term future and then tasks technical specialists at the Field Centers to develop plans in these areas. These plans become inputs to the technology managers at the Centers as they formulate the Enterprise Technology Plans and are subsequently reviewed by the TLC as part of the process for developing recommendations for technology priorities and a NASA budget for technology. OCT is also responsible for the development of the NASA Technology Plan and the associated NASA Technology Inventory (described in Section 2.3).

OCT supports the review activities of the Technology and Commercialization Advisory Committee (TCAC), a standing committee of the NASA Advisory Council. The TCAC advises NASA on broad, Agencywide issues associated with technology and commercialization activities. In addition, each Enterprise supports an advisory committee that is part of the NASA Advisory Council to review its programs and provide recommendations for improvement. These advisory committees include technologists or, in some cases, technology subcommittees to provide special focus on technology activities.

2.3 NASA Technology Structure

The NASA Strategic Plan establishes the goals and strategy for the Agency and identifies top-level goals for each Enterprise. Each Strategic Enterprise works with its respective customer and user

community to translate these broad goals into Enterprise missions and programs and to formulate technology challenges for potential future missions. The Enterprise technology leaders then work with Technology Integrators at the NASA Field Centers to develop specific technology programs to meet the technology challenges. All NASA technology programs are funded through an Enterprise and are integrated into one of the four Enterprise programs. The Technology Integrators responsible for planning and integrating the technology components of each of the Enterprise programs collaborate to take advantage of synergy among the Enterprise technology goals and to ensure that duplication of efforts does not occur.

The integration of technology within the Enterprises ensures that technology programs are closely aligned with Enterprise mission goals, frequently referred to as "mission pull," but this raises a concern that technology programs will evolve toward nearer term goals and incremental improvements rather than longer term strategic goals that are more revolutionary. To balance this mission-pull pressure, NASA has identified a group of "technology push" areas that are strategically important to achieving ambitious future NASA missions. Six of these areas are identified as Strategic Technology Areas and include advanced miniaturization, intelligent systems, compact sensors and instruments, self-sustaining human support, deep space systems, and intelligent synthesis environments. Four additional technology areas align closely with sectors of the commercial aerospace industry (space transportation, communications, remote sensing, and in-space processing) and are designated Space Industry Sectors.

Plans for each of the Strategic Technology Areas are developed by technology focal points at the Field Centers who are recognized technical experts in their respective areas. These plans describe a revolutionary vision of the future, but they also include specific goals and measurable milestones for near-term as well as far-term objectives. These plans are prepared for OCT, reviewed by the TLC, and then submitted to the Technology Integrators for each of the Enterprises as an input to their planning process. This process is diagrammed in Figure 2.3-1.

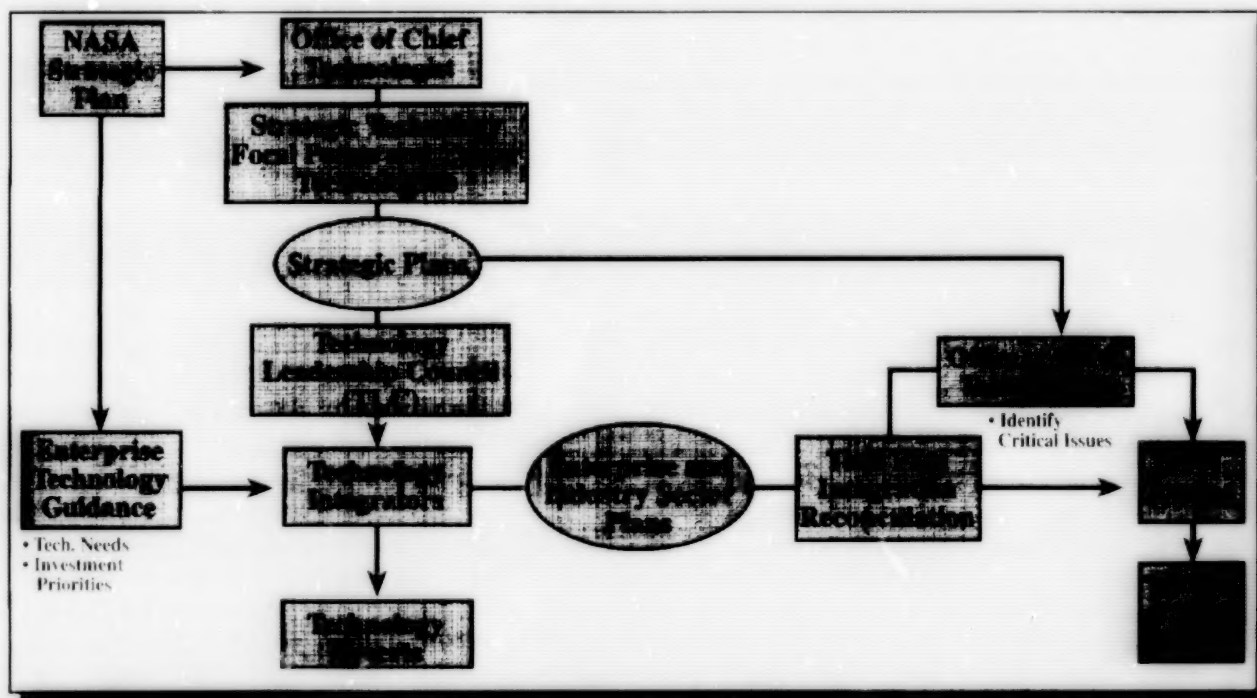


FIGURE 2.3-1. NASA TECHNOLOGY PLANNING PROCESS ELEMENTS

Plans for the Space Industry Sectors are prepared by Center technologists in concert with industry, consistent with the investment strategy discussed earlier in Section 1.4. These plans are also reviewed by OCT and the TLC to ensure that they contain sufficient long-term technology goals and investments. However, the various Space Industry Sectors align closely with specific Enterprises, so these plans become a component of the respective Enterprise Technology Plans.

Following their preparation, the Enterprise Technology Plans are reviewed by OCT and the TLC to assess their responsiveness to the Strategic Technology Area Plans and the Space Industry Sector Plans. OCT identifies critical issues for TLC consideration, and these may be incorporated into the recommendations for budget and technology priorities that the TLC provides to the Capital Investment Council as part of the budget cycle input.

Although the NASA technology program is broad in scope and character, there is an urgent need for simple tools to analyze and communicate the content of the program to a variety of potential partners and users both inside and outside NASA. One response to this need is the NASA Technology Inventory, a comprehensive data base of information on individual programs and projects that could be interrogated for specific information. An effort to assemble this data base is under way and partially completed. A hierarchy has been developed to promote consistency of input data and also to build a linkage between individual projects and Enterprise goals. Table 2.3-1 identifies the levels in the hierarchy and provides an example entry from one Enterprise.

The mission area is a broad area of scientific endeavor in response to fundamental scientific questions. The challenge translates the scientific questions into corresponding quantified engineering goals. The concept level describes the competing concepts that show potential for achieving the challenge. For each concept, there may be one or more technology needs that cannot be met with existing capabilities. Finally, the individual data base entry at the technology program or project level describes the technology effort in terms of objective, goal, approach, milestones, resources, TRL, relationship to Strategic Technology Areas and Space Industry Sectors, implementing organization and contact points, and so forth. The NASA Technology Inventory will be available to the public through a web-based server linked to the web site of OCT (see Appendix D). The inventory will include a search engine and will provide a complete look at NASA's technology program.

TABLE 2.3-1. HIERARCHICAL ORDER OF NASA TECHNOLOGY INVENTORY

<i>Hierarchy</i>	<i>Example</i>
Enterprise	• Space Science
Mission Area	• Astronomical Search for Origins
Challenge	• Detect Earth-like Planets at 10-15 par secs
Concept	• 100 meter Baseline IR Interferometer, 4x(1-2)m Apertures
Technology Need	• Sub-Picometer Metrology for 10 ⁶ Nulling of Central Star • Precision Deployable Beam Structures
Technology Program Project	• Optical Delay Lines • Submicron Precision Rotating Joints

2.4 Technology Investment Budget

The NASA fiscal year 1998 investment in advanced technology is shown in Figure 2.4-1. The data in the figure identify the resources provided for technology in principal program areas. The program areas relate directly to NASA Enterprises, except for the Small Business Innovation Research and the Other areas. Funds in these areas support work for all four Enterprises. The figure also includes estimates of the technology content of scientific or development activities, so the data depend on the definition of technology and are not directly traceable to NASA budget line data. The NASA budget structure at the project level does not currently include Government employee salaries and some overheads.

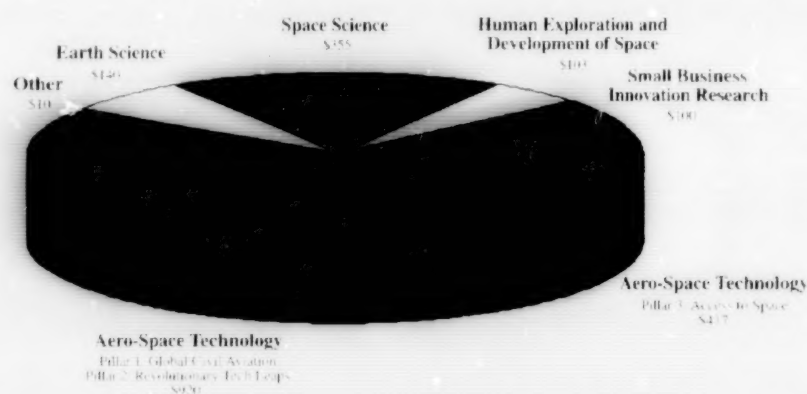


FIGURE 2.4-1. DISTRIBUTION OF THE \$2.0 BILLION FISCAL YEAR 1998 TECHNOLOGY INVESTMENT (CIVIL SERVANT SALARIES AND SOME RELATED OVERHEADS ARE NOT INCLUDED; DOLLARS IN MILLIONS)

2.5 Technology Coordination and Review

This section describes coordination and review relationships between NASA and other Government agencies across aeronautics and space technology. The activities summarized do not cover all interagency relationships, but they are focused on major Agency-level activities. Aeronautics activities are presented first, followed by those for space technology.

A key element of NASA's overall technology strategy is to work cooperatively and in partnership with other Government agencies. Since the creation of the Agency in 1958, NASA has had a close, collaborative relationship with the Federal Aviation Administration (FAA) and the Department of Defense (DOD) in developing advanced aeronautics technology for improved performance, greater safety, and lower cost.

NASA and the FAA have cooperated over the past two decades primarily through an FAA-NASA Coordinating Committee. In 1990, a letter of agreement was signed between the two agencies to establish a top-level framework for addressing critical national issues. Currently, there are memoranda of understanding covering seven areas of cooperation:

- Cockpit-air traffic control integration research
- Human factors research
- Severe weather research
- Environment compatibility research
- Airworthiness research
- Airspace system user operational flexibility
- Program support to strengthened the overall working relationship

NASA's extensive cooperation and coordination with DOD includes both formal and informal arrangements. The Agency has specific agreements encompassing: flight testing to exploit NASA leadership in this area at the Dryden Flight Research Center; U.S. Army rotorcraft research at the Ames Research Center, Langley Research Center, and Lewis Research Center; and aging aircraft at Langley. NASA also coordinates technology development programs with the U.S. Air Force through their Joint Aeronautical Commanders Council. Other significant activities include cooperation with the U.S. Navy in aeroelasticity and the Air Force in advanced aircraft engine technology.

Similarly, NASA's cooperation with DOD in space technology has existed since the beginning of the Agency and is specified in the Space Act of 1958 that created NASA. Over the past few years, NASA has significantly increased its level of cooperation with the National Reconnaissance Office (NRO) because of their expanded ability to interact with a broader technology community. Both DOD and the NRO are investing heavily in advanced space technology with goals and objectives that, in many cases, align closely with those of NASA. NASA, DOD, and the NRO are uniformly placing a very high priority on:

- Reducing the cost of missions by reducing the size, weight, and power requirements of spacecraft and instruments, which in turn allows the use of smaller, lower cost launch vehicles
- Lowering operating cost by incorporating much higher levels of "intelligence" into spacecraft and instruments
- Reducing development time to be more responsive to mission opportunities
- Pursuing innovative systems architecture, concepts, and technology that can significantly improve performance and open new mission opportunities

Agency-level cooperation with DOD and the NRO is being pursued primarily through two strategic activities. The first is based on a special study initiated in the summer of 1995 within the scope of the NASA-DOD Aeronautics and Astronautics Coordination Board (AACB). The AACB was established in 1960 to promote cooperation between the two organizations at the strategic level and is chaired by the DOD Under Secretary for Research and Engineering and the NASA Deputy Administrator. The special study activity reconfirmed NASA as the lead organization for Reusable Launch Vehicle technology and DOD for Expendable Launch Vehicle technology, with specific recommendations to improve this relationship. It also identified several opportunities for increased cooperation in spacecraft technology that could significantly benefit both NASA and DOD, including space flight experiments, large space optics, microminiaturization, spacecraft autonomy, data processing/fusion, space structures, radiation-hardened electronics, and infrared detectors.

More recently, and consistent with the AACB initiative, NASA, DOD, and the NRO have formed a Space Technology Alliance to assure continued dialog, information exchange, and direct cooperation in the development of advanced space technology. The alliance is chaired by senior technology managers from all three organizations. NASA's co-chair is the Chief Technologist. The near-term activities of the alliance include creating an overall space technology framework to improve long-term cooperation.

NASA is also heavily involved in broad-based, multi-agency activities to advance the Nation's computing through an information networking infrastructure, including the High Performance Computing and Communication Initiative focused on developing teraflop computing (primarily with the Department of Energy), a far-reaching program to develop even faster petaflop computing, and the Next Generation Internet (with DOD, the Department of Energy, the Department of Commerce, and the National Science Foundation) to dramatically increase the span and rate of network communications.



3.0 NASA Enterprise Technology Needs

The NASA Strategic Plan provides NASA's vision of the future and defines how the four Strategic Enterprises and their associated Field Centers contribute to accomplishing that vision. In turn, each of the Enterprises works with its customer community to translate the vision into a roadmap (Appendix C), which includes goals, objectives, and major milestones for three timeframes in the future. Advanced technology is a critical component of each of these Enterprise roadmaps, and their technology programs are focused on technology needs that are driven by the Enterprise vision. This section of the plan addresses each Enterprise in turn, and it builds on the technology goals identified in the Enterprise roadmap by providing additional information on how these mission-pull technology needs are derived. More details on these technology needs and how they are derived can be found in the Enterprise Strategic Plans.

3.1 Space Science Enterprise

Space Science Program Planning

The Space Science Enterprise (SSE) Strategic Plan (see Appendix D) begins with a set of seven fundamental questions that address what we are trying to achieve at the highest level. These Space Science fundamental questions are a more detailed scientific formulation by the space science community of two of Administrator Daniel Goldin's set of fundamental questions for NASA:

How did the universe, galaxies, stars, and planets form and evolve? How can our exploration of the universe and our solar system revolutionize our understanding of physics, chemistry, and biology?

Does life in any form, however simple or complex, carbon-based or other, exist elsewhere than on planet Earth? Are there Earthlike planets beyond our solar system?

SSE also contributes to answering two additional questions of Administrator Geldin:

How can we utilize the knowledge of the Sun, Earth, and other planetary bodies to develop predictive environmental, climate, natural disaster, and natural resource models to help ensure sustainable development and improve the quality of life on Earth?

What cutting-edge technologies, processes, and techniques and engineering capabilities must we develop to enable our research agenda in the most productive, economical, and timely manner? . . .

To address the fundamental questions, SSE—guided by the National Academy of Science and the space science community—has formulated broad Enterprise goals, specific science goals that guide our efforts over the next decade or two, and detailed science objectives that can be accomplished within the next 5 to 6 years through one or more space missions and ground-based programs. The SSE Strategic Plan proposes near-term (2000–2004) and long-term (2005–2020) missions and programs to address the fundamental questions, science goals, and science objectives.

Space Science Technology Planning

Technology is pivotal for reducing significantly spacecraft development cost and time and significantly increasing the number of missions launched each year. It is clear that new technology is critical to enable the new levels of performance and capability required by the current set of planned space science missions.

The Strategic Plan shows that SSE designs its technology program to pursue five Technology Goals by means of advancements in 10 key capabilities. The Technology Goals are:

1. Lower mission life-cycle costs and provide critical new capabilities through aggressive technology development
2. Develop innovative technologies to address far-term scientific goals, spawn new measurement concepts and mission opportunities, and create new ways of doing space science
3. Develop and nurture an effective science-technology partnership to help optimize mission concepts and infuse new technologies into science missions, with the goal of dramatically lowering mission cost and risk
4. Stimulate cooperation among industry, academia, and Government to ensure that the Nation can reap the maximum scientific and economic benefit from its space science mission and technology programs
5. Identify and fund the development of important crosscutting technologies that support space science and the other NASA Enterprises

The 10 Key Capabilities for Space Science Missions identified in the SSE Strategic Plan represent the SSE technology needs. They are:

Key Capabilities for Space Science Missions

- | | |
|--|---------------------------------------|
| • Advanced Structures Deployment and Control | • Power |
| • Communications | • Sample Acquisition and Return |
| • Design Tools and Spacecraft Operability | • Science Instruments |
| • Lightweight Optics | • Spacecraft Systems and Intelligence |
| • Metrology | • Transportation and Mobility |

The identification of these capabilities proceeded from four roadmapping studies (one for each of the SSE science themes) conducted in 1996 and early 1997. The studies were performed by extensive teams of space scientists and technologists and included members from each of the three groups within the space science community: universities, industries, and NASA Centers.

Each science and technology roadmap begins with a statement of the "Quests"—broad endeavors designed to answer the fundamental scientific questions on which the strategy of the Enterprise is based. At the core of each roadmap is a set of reference missions—sometimes also called *portrait missions*. This set, although not necessarily containing actual missions, was judged by the teams of experts as representative and adequate to satisfy the Quests. Then the teams identified the technology advancements required to conduct the reference missions, as shown in Table 3.1-1. In May 1997, SSE invited a large group of leaders in space science and technology to a special workshop in Breckenridge, Colorado, to formulate the SSE Strategic Plan for 2000-2004 and beyond. The 10 Key Capabilities for Space Science Missions represent the workshop's consolidation of the technology roadmaps.

TABLE 3.1-1. SPACE SCIENCE ENTERPRISE KEY TECHNOLOGY CAPABILITIES ENABLE OR ENHANCE FUTURE MISSIONS

Enterprise Key Capabilities	Future Missions									
	Solar Terr. Probe	Solar Probe	Europa Orbiter, P-K Exp.	Mars Survey	New-Gen. Space Telescope	Space Interfer. Mission	Terr. Planet Finder	Far IR Submm Telescope	Gamma-Ray Telescope	Constellation X-Ray
Structures					A	A	A	H		
Communic.	H	H	H	H	H	H	H	H	H	H
Design Tools	H	H	H	H	A	A	A	H	H	H
Light Optics					A	A	A	A		
Metrology					A	A	A			
Power	H	A	H	H	H	H	H	H	H	H
In situ Sampling				A						
Instruments			H	H	A	A	A	A	A	A
Spacecraft Systems										
Intel	H	H	H	A	A	A	A	A	H	H
Mobility		H	H	A						

Note: H = Enhance, A = Enable

SSE recognizes the intimate interaction between technology development and mission studies. On one hand, the Enterprise has consolidated management of these two activities in a single division; on the other hand, it has adopted the policies that each space science mission contribute to the advancement of technology and that adequate technology be demonstrated before a mission is approved for development.

The intimate relationship between mission studies and the Technology Program manifests itself in the evolution of technology-push efforts formulated in response to broadly conceived technical challenges derived from the science goals. If this work—at a low Technology Readiness Level (TRL)—confirms the fundamental validity of the technical approach, its initial findings and parameters are incorporated in pre-Phase A studies to determine its usefulness in a preliminary mission setting.

These studies, in turn, provide more complex and constraining conditions that laboratory and test-bed validations of the approach under study must satisfy. Gradually, the emphasis shifts from *technology-push* to *mission-pull* as the technology graduates to ground or space-based system demonstrations designed to provide confidence that the planned application of the technology will meet the project requirements.

Continuing analyses and mission studies since the Breckenridge workshop have refined the detailed content of each of the 10 key capabilities, as indicated in Table 3.1–2 (see Section 6.3 for quantitative data on current status and future milestone accomplishments planned for these technologies).

TABLE 3.1–2. DETAILS OF KEY CAPABILITIES FOR SPACE SCIENCE MISSIONS

<ul style="list-style-type: none"> • Advanced Structures Deployment and Control <ul style="list-style-type: none"> ▷ Large Lightweight Nonprecision Structures ▷ Lightweight Optically Precise Structures ▷ Advanced Lightweight Materials • Communications <ul style="list-style-type: none"> ▷ Microcommunications Radio Frequency Systems ▷ Optical Communications Systems ▷ High-Rate Radio Frequency Systems and Components • Design Tools <ul style="list-style-type: none"> ▷ User Interfaces ▷ Collaborative Design Infrastructure ▷ Integrated Design and Simulation Tools ▷ Verification and Validation • Lightweight Optics <ul style="list-style-type: none"> ▷ Large Lightweight Mirrors ▷ Deployable Telescopes ▷ Optical Control Systems ▷ Instrument Optics Components • Science Instruments <ul style="list-style-type: none"> ▷ Submillimeter and Microwave Instruments ▷ Ultraviolet, Visible, and Infrared Instruments ▷ Spectrometer and Radiometer Systems ▷ High-Energy Instruments ▷ Active Optical Systems ▷ Radar Systems ▷ In Situ Systems ▷ Cryocoolers and Cryogenic Systems 	<ul style="list-style-type: none"> • Metrology <ul style="list-style-type: none"> ▷ Vibration Control Systems ▷ Precision Active Systems ▷ Precision Actuators • Sample Acquisition and Return <ul style="list-style-type: none"> ▷ Sample Selection and Acquisition Systems ▷ Sample Preparation and Storage Systems ▷ Sample Recovery and Quarantine • Power <ul style="list-style-type: none"> ▷ Energy Storage Systems ▷ Power Conversion ▷ Photovoltaic Power Systems ▷ Nuclear Power Systems • Spacecraft Systems and Intelligence <ul style="list-style-type: none"> ▷ Advanced Spacecraft Architectures ▷ Instrument and Spacecraft Computing Systems ▷ Guidance, Navigation, and Control Sensors and Actuators ▷ Autonomous Science Algorithms and Architectures ▷ Autonomous Operations Components and Algorithms • Transportation and Mobility <ul style="list-style-type: none"> ▷ Onboard Spacecraft Propulsion ▷ Surface Mobility and Navigation Systems ▷ Atmospheric Mobility and Navigation Systems ▷ Subsurface Mobility Systems ▷ Aeronomy, Aerocapture, and Aeroassist Systems ▷ Planetary and Small Body Ascent Propulsion Systems
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3.2 Earth Science Enterprise

The Earth Science Enterprise (ESE) is dedicated to understanding the total Earth system and the effects of natural and human-induced changes on the global environment. ESE addresses the fundamental question:

How can we utilize the knowledge of the Sun, Earth, and other planetary bodies to develop predictive environmental, climatic, natural disaster, and natural resource models to help ensure sustainable development and improve the quality of life on Earth?

As part of the Agency Crosscutting Process called Providing Aerospace Products and Capabilities, ESE addresses the questions:

What cutting-edge technologies, processes, techniques and engineering capabilities must we produce to enable our research agenda in the most productive, economical, and timely manner? How can we most effectively transfer the knowledge we gain from our research and discoveries to commercial ventures in the air, in space, and on Earth?

The goals of ESE are:

- Expand scientific knowledge of the Earth system using NASA's unique vantage points of space, aircraft, and in situ platforms, creating an international capability to forecast and assess the health of the Earth system
- Disseminate information about the Earth system
- Enable the productive use of Earth science and technology in the public and private sectors

Science Research Strategy

The ESE Science Research Plan targets five specific research issues for focused investment of program resources during the next 5 years. These themes are tied to the interagency U.S. Global Change Research Program and/or the National Space Policy Presidential Decision Directive. The five research themes are:

- Land-Cover/Land-Use Change and Global Productivity Research
- Seasonal-to-Interannual Climate Variability and Prediction
- Long-Term Climate: Natural Variability and Change Research
- Atmospheric Ozone Research
- Natural Hazards Research and Applications

ESE employs a strategy that:

- Establishes science priorities with near-term product milestones on a path of long-term inquiry

- Develops advanced technologies that lead to new and lower cost scientific investigations
- Promotes extensive international collaboration and cooperation with other Federal agencies
- Contributes to national and international assessments of the environment
- Fosters commercial use of remote-sensing data and leverages the resources of the commercial remote-sensing industry to lower overall ESE costs
- Strengthens Earth science education and public awareness

The development of advanced technology will play a major role in shaping the ESE program of the future. The Enterprise will use technology development as a means to accomplish its current programs more efficiently and stimulate new programs necessary to meet its long-term goals.

Technology Program Strategy

ESE is establishing the ESE Technology Development Program to consolidate and focus its technology investments. The goal of the ESE Technology Development Program is to reduce the overall cost to the Enterprise while enhancing its effectiveness, enabling new science, and transferring mature research endeavors to operational Government agencies or into commercial products and services.

The investment strategy for the ESE Technology Development Program provides a framework for setting priorities among competing capability needs and among diverse technology solution options. The planning, implementation, and assessment of the technology program incorporate six strategic elements to optimize the benefits to the Enterprise:

- Maintain a traceable link between science objectives and technology
- Ensure overall program cost-effectiveness through technology advances and application
- Implement a technology development program appropriate to support 3-year acquisition time lines for flight and ground systems
- Ensure that Enterprise technology programs consider near-, mid-, and far-term horizons
- Ensure cross-Enterprise program synergy and external partnerships to better leverage Enterprise technology investments
- Focus Enterprise resources on critical, high-payoff ESE technology needs through an integrated technology planning process

ESE has implemented a systematic process to identify and prioritize its technology needs. Science priorities and measurement continuity requirements drive the process. The process retains a clear connection between these measurement goals and the derived technology performance requirements.

Technology Program Elements

As a result of this process, the Enterprise has expanded the science research themes into a set of challenges that represent specific Earth Science measurement areas or systems. In addition, the Enterprise has identified technology concepts that implement those measurements. The concepts range from instrument systems and subsystems to measurement techniques. The concepts are not characterized by maturity level and, in fact, vary significantly in TRL. Figure 3.2-1 summarizes

In addition to specific measurement technologies, ESE is pursuing a spacecraft and information systems technology strategy that is applicable to all science research themes. Figure 3.2-2 summarizes the relationship between the broad Earth science technology goals and the resulting implementation concepts.

Theme Areas							
	Land Cover/Global Productivity/Land Use	X	X	X	X	X	X
	Ozone/Chemistry	X	X	X	X	X	X
	Interannual Climate	X	X	X	X	X	X
	Long-term Climate	X	X	X	X	X	X
	Natural Disasters	X	X	X	X	X	X
							
		Challenges					
		24	25	26	27	28	29
		Reduce the cost of future ESE space missions					
		Reduce instrument costs and spacecraft acc. requirements					
Concepts	Advanced Global Positioning System methods	HH	X	X	X		
	Autonomous stationkeeping	II			X		X X
	Precise interspacecraft metrology	JJ			X		X X
	Advanced batteries that provide 60 W-hr/kg for 30,000 cycles	KK	X	X	X		X
	High-efficiency (>20% i, lightweight (>50W/kg) solar arrays	LL	X	X			X
	Atomic oxygen resistance materials effective in low-Earth orbit	MM	X	X			X
	Radiation hardened processors and data storage devices	NN			X		X
	Advanced software	OO	X	X		X	X
	High speed radio frequency or optical data transmission systems	PP			X	X	
	Advanced data display and visualization systems	QQ				X	X

FIGURE 3.2-2. MAPPING OF SPACECRAFT AND INFORMATION SYSTEMS TECHNOLOGIES TO EARTH SCIENCE TECHNOLOGY GOALS

Three major areas of focus for technology investment are derived from the following concepts:

- I. Advanced instrument and measurement technologies for new and/or lower cost scientific investigations that will expand scientific knowledge of the Earth system using NASA's unique vantage points of space, aircraft, and in situ platforms. These include:
 - Instrument and sensor architectures that provide significant reductions in the end-to-end implementation costs by decreasing mass, launch volume, power, and operation complexity for the whole spectrum of Earth-observing instruments
 - Instrument and sensor architectures that enable new, high-priority science in support of the ESE research themes
 - Active sensors for space-based lidar and radar applications with improved lifetime, efficiency, and performance, as well as with reduced mass, launch volume, and cost

- Detector arrays and passive sensing systems covering the wavelength bands of interest to Earth science that reduce instrument accommodation requirements and simplify calibration, integration, and operations
 - Miniature, self-contained instrument packages for in situ and remote-sensing measurements from aircraft, balloons, ocean buoys, etc.
2. Cutting-edge technologies, processes, techniques, and engineering capabilities that reduce development and operations costs and that support rapid implementation to support productive, economical, and timely missions. These include:
- Techniques and algorithms that enable the achievement of science objectives by formation flying of small spacecraft, including calibration and data fusion considerations
 - Mechanical and electronic innovations that simplify design, fabrication, and operation and provide significant reductions in spacecraft system and subsystem resource requirements
 - Increased levels of spacecraft and/or ground system autonomy that streamline operations and that simplify and reduce the cost of command, control, and monitoring of the flight segment
 - Onboard data fusion and interinstrument data comparison for autonomous, multi-instrument campaigns and onboard, adaptive data acquisition strategies combining multiple resources, including multiple spacecraft, airborne, and ground capabilities
3. Advanced end-to-end mission information system technologies for collecting and disseminating information about the Earth system and enabling the productive use of ESE science and technology in the public and private sectors. These include:
- Improvements in collecting, compressing, transmitting, processing, distributing, and archiving data from all Earth remote-sensing and in situ sensing assets
 - Effective approaches for linking multiple data sets and for extracting and visualizing information on the global Earth system

ESE recognizes the potential of emerging technology breakthroughs to enable previously unenvisioned approaches for addressing Enterprise science priorities. NASA will seek and exploit these *technology-push* opportunities through Enterprise and cross-Enterprise advanced concepts programs.

Alignment to Strategic Technology Areas and Space Industry Sectors

ESE's technology development needs are closely aligned with the Agency Strategic Technology Areas and Space Industry Sectors, as follows:

- Advanced miniaturization will enable smaller, more capable missions in space, as well as on radiosondes, unpiloted air vehicles, ocean buoys, etc.
- Intelligent systems will enable the cooperative and adaptive use of multiple remote-sensing and in situ sensing assets to respond to a dynamic Earth with minimum human interference.

- Compact sensors and instruments are the hearts of any Earth science measurement system, and advances in these technologies will enable smaller missions and opportunities to leverage commercial and other cooperative mission opportunities.
- Although self-sustaining human support does not directly apply to Earth science technology needs, some synergy exists among the sensing, monitoring, and modeling needs of this area and ESE.
- Similarly, the deep space systems area will develop systems tolerant to conditions that could support Earth science in the exploration of volcanoes, the deep oceans, and other extreme environments.
- The intelligent synthesis environment, in addition to streamlining the development of missions, will directly support the collaborative scientific endeavor needed to address the Enterprise's 25-year focus of expanding scientific knowledge by forecasting and assessing the state of the Earth system with regional accuracy on decadal time scales.

Equally critical for ESE are the opportunities for partnership with and reliance on the Space Industry Sectors for the advancement and application of new technologies. The space transportation sector will provide the access to space that is essential to the implementation of the ESE program. The emerging capabilities of the space communications and commercial remote-sensing sectors will provide the spacecraft bus capabilities through mechanisms such as the Rapid Spacecraft Procurement contract. In addition, the proliferation of space communications assets in a variety of orbits allows the opportunity for partnerships, piggyback payloads, and other cooperative activities. This proliferation will also allow an increased reliance on commercial communications systems to link space-based and in situ (for example, ocean buoy and long-duration balloon) systems. Finally, as NASA research demonstrates the value of key measurements, the Agency expects to transition research measurements to viable commercial enterprises. This will allow NASA to leverage the capabilities of the emerging remote-sensing industry while reducing Agency costs and enhancing national competitiveness.

3.3 Human Exploration and Development of Space Enterprise

The Human Exploration and Development of Space (HEDS) Enterprise, which comprises both the Office of Space Flight and the Office of Life and Microgravity Sciences and Applications, will implement and support research, technology, and systems development projects in pursuit of the Agency's fundamental questions. The HEDS Enterprise addresses the fundamental question:

What is the fundamental role of gravity and cosmic radiation in vital biological, physical, and chemical systems in space, on other planetary bodies, and on Earth, and how do we apply this fundamental knowledge to the establishment of permanent human presence in space to improve life on Earth?

As part of the Agency Crosscutting Process of Providing Aerospace Products and Capabilities, the HEDS Enterprise also addresses the question:

What cutting-edge technologies, processes, techniques and engineering capabilities must we produce to enable our research agenda in the most productive, economical, and timely manner? How can we most effectively transfer the knowledge we gain from our research and discoveries to commercial ventures in the air, in space, and on Earth?

The four broad strategic goals of the HEDS Enterprise are:

1. Explore the role of gravity in physical, chemical, and biological processes
2. Prepare to conduct human missions of exploration
3. Continue to open and develop the space frontier
4. Aggressively seek investment from the private sector

In pursuit of its strategic goals, the HEDS Enterprise will undertake several subgoals and objectives that bear materially on its technology research and development needs. For example, to explore the role of gravity in physical, chemical, and biological processes, the HEDS Enterprise intends to enable the research community to use gravity as an experimental variable. Also, in preparing to conduct human missions of exploration, HEDS will work in partnership with SSE to carry out an integrated program of robotic exploration of the solar system to characterize the potential for human exploration and development. In addition, the Enterprise will explore an investment in enabling crosscutting technology and studies that can affordably open up the frontiers for human space exploration where there is a compelling rationale for human involvement.

As it continues to open and develop the space frontier, HEDS will develop and assemble the International Space Station (ISS) and use it to advance scientific, engineering and technology, exploration, and commercial activities. This will entail deploying and operating the ISS for research, engineering, and exploration activities, as well as ensuring the health, safety, and performance of space flight crews. The Enterprise will also seek to provide safe and affordable human access to space. This will involve improving Space Shuttle operations by safely flying the manifest and aggressively pursuing a systems upgrade program.

Finally, to seek investment from the private sector aggressively, HEDS will strive to increase the affordability of space operations through privatization and commercialization. This will involve promoting investments in ISS utilization capabilities and in ISS system and operations capabilities as pathfinders in ISS commercial operations. Cost reductions in Space Shuttle operations will be sought through privatization, eventual commercialization, and the flying of cost-reimbursable payloads. Privatization and eventual commercialization will also be used to reduce space communications and operations costs. In addition, the Enterprise will seek to foster consortia of industry, academia, and Government; to leverage funding, resources, and expertise; and to identify and develop space commercial opportunities.

In accomplishing its strategic goals and objectives, the HEDS Enterprise implements and supports a diverse set of programs, projects, and initiatives spanning several NASA offices. These efforts include the Space Shuttle Program (SSP), the ISS, life and microgravity sciences programs, space operations and communications, materials processing research in microgravity and other commercial development of space efforts, engineering and technology testbed activities, advanced

space transportation systems, and the human exploration of space. The Enterprise involves an equally broad and challenging set of technology needs, ranging from the immediate future to the second decade of the next century.

These diverse HEDS activities support the resolution of NASA's strategic questions in three key ways:

1. Conducting HEDS scientific and exploration activities
2. Providing vitally needed infrastructure and operational support to the other NASA Enterprises in their science programs
3. Developing scenarios and technical requirements in partnership with the other NASA Enterprises relating to the human exploration and development of space over the long term

For example, HEDS provides critically needed infrastructure, such as the Space Shuttle, which has enabled the enormously successful Hubble Space Telescope program by making in-space servicing possible. The ISS will provide a large, crewed, and logistically supported platform in space that will cost-effectively enable certain types of astronomical observation experiments (for example, the Antimatter Spectrometer). HEDS also provides key infrastructure and operational support (in particular, space communications services) to support a broad range of space science and Earth science efforts. HEDS works in close partnership with SSE to define nearer term robotic missions, as well as formulating innovative approaches to eventual human exploration and intensive scientific research on other planets (e.g., Mars).

The HEDS Enterprise is making near-term investments and examining long-term options and concepts that relate to enabling "revolutionary technological advances to provide air and space travel for anyone, anytime, anywhere more safely, more affordably, and with less impact on the environment and improve business opportunities and global security." These efforts include moving to private operation of the Space Shuttle in the near term, while continuing to invest in upgrades of the Space Shuttle system, and for farther term needs, examining options for more highly automated, lower cost "space port" operations.

At the present time, HEDS is focusing its future human exploration efforts on the study of options through a small cadre of civil service employees. In the longer term, the Enterprise anticipates that as ISS schedule milestones are achieved, advanced technology initiatives will be formulated to invest in "cutting-edge technologies, processes, techniques, and engineering capabilities to enable our research agenda in the most productive, economical and timely manner," while helping to answer the question: How can we most effectively transfer the knowledge we gain from our research and discoveries to commercial ventures in the air, in space, and on Earth? The following section provides a summary of the technology needs of the HEDS Enterprise.

Strategic Goal 1: Exploring the Role of Gravity in Physical, Chemical, and Biological Processes

The HEDS Enterprise will conduct an effective program of in-space research related to the role of gravity in physical, chemical, and biological processes and the pursuit of discoveries related to the origin, evolution, and destiny of life. These in-space efforts will be founded on a robust ground research program. To accomplish these objectives, missions will be flown on the Space Shuttle,

the ISS, and elsewhere. A diverse set of technology developments will be needed, many of which may be appropriate for support from the various NASA technology programs (such as the Crosscutting Technology Development Program). In particular, the central challenge for HEDS technology research and development in this area will be to detect and measure the effects of gravity and the space environment on biological, chemical, and physical processes, as well as on living organisms. (The development of these technologies will also support HEDS Strategic Goal 2.)

To reduce costs and enhance scientific returns from microgravity payloads on the Space Shuttle and the ISS, advanced data handling, control, and communications technologies are needed. These technology requirements include high-bandwidth ground-to-space communications (potentially provided by optical communications technologies), the fusion of dissimilar data types, and advanced video processing, as well as improved ground-based data networks. In addition, increasingly advanced software and data management systems are needed to allow for remote operations (ground-based control), as well as more autonomous on-orbit operations. For some applications, advanced telerobotics technologies (in particular, micromanipulators) will be needed.

Advanced vibration isolation technologies (both passive and active) could significantly improve the scientific returns from future microgravity research projects—in particular, in the use of the ISS for such studies. In addition, technology development for high-temperature microgravity heat pipe technology (directed toward advanced furnace liners) is essential future solidification research. As noted below, implantable miniaturized biotelemetry sensors are required to enable the unrestrained monitoring of physiological parameters in rodents and small primates over periods of weeks. Similarly, miniaturized biotelemetry sensors and systems are needed for the scientific monitoring of human crew subjects. Table 3.3-1 provides a summary of HEDS strategic technology needs associated with exploring the role of gravity in physical, chemical, and biological processes.

TABLE 3.3-1. SUMMARY OF STRATEGIC TECHNOLOGY REQUIREMENTS THAT ARE DRIVEN BY EXPLORATION OF THE ROLE OF GRAVITY IN PHYSICAL, CHEMICAL, AND BIOLOGICAL PROCESSES

<i>Technology</i>	<i>Timeframe and Mission Class for Which TRL-5 Is Needed</i>		
	<i>Near-Term</i>	<i>Midterm</i>	<i>Far-Term</i>
High-Bandwidth Communications	Space Shuttle-Based Expts.	ISS Expts.	ISS Expts.
Mini-Biosensor Systems (Animals)	Space Shuttle-Based Expts.	ISS Expts.	ISS Expts.
Mini-Biosensor Systems (Humans)	Space Shuttle-Based Expts.	ISS Expts.	ISS Expts.
AI/Expert Systems for On-Orbit Operations	—	ISS Expts.	ISS Expts.
Active/Passive Vibration Isolation	—	ISS Expts.	ISS Expts.
High-Temperature Microgravity Heat Pipe	—	ISS Expts.	ISS Expts.
Portable Clinical Lab Systems (Animals)	—	ISS Expts.	ISS Expts.
Portable Clinical Lab Systems (Humans)	—	ISS Expts.	ISS Expts.

Strategic Goal 2: Preparing to Conduct Human Missions of Exploration

The HEDS Enterprise plans to define architectures and requirements for human exploration that radically reduce the costs of such missions through the use of advanced technologies, commercial partnerships, and innovative systems strategies. In addition, the Enterprise will collaborate with

SSE to acquire needed early knowledge about Mars via robotic missions and will advance biomedical knowledge and technologies in preparing for future missions.

There are a number of technology challenges facing HEDS as it seeks to accomplish this goal. For example, technologists must develop scenarios, concepts, and technological approaches that achieve at least an order-of-magnitude reduction in the costs of nontransportation systems for the human exploration beyond Earth orbit, compared to 1990 projections. (Research and development in this area will also support HEDS Strategic Goal 3.) Technologists must also achieve an order-of-magnitude reduction in space program operations costs compared to 1990 levels. (Research and development in this area will also support HEDS Strategic Goals 3 and 4.)

In addition, research and development must result in the development of safe, self-sufficient, and self-sustaining advanced technologies and systems that can enable humans to live and work in space and on other planets, independent from Earth, for extended periods of time. Research and development related to this challenge would also support HEDS Strategic Goal 3. Moreover, HEDS must develop technology to enable improved understanding of, and more effective and efficient protection from, galactic cosmic rays and solar particles events for machines, humans, and other living organisms, as well as develop technology to support noninvasive, long-term monitoring and in situ maintenance of human health and to sustain the performance of humans in space. In addition, technology development must empower extended human presence in space via a deep symbiosis between humans and machines. R&D in these areas will also support HEDS Strategic Goal 3.

A wide variety of specific technologies will be needed to support the design, development, and ultimate implementation of human expeditions beyond low-Earth orbit. These include many systems-level technologies, such as extravehicular activity (EVA) systems, and a host of component-level technologies (such as advanced scientific, environmental, and operational sensors and related information-processing software and systems). Some of the technology areas that need to be addressed include crew health and performance, in situ resource utilization, advanced communications and operations, advanced power systems, autonomous systems and robotics, advanced life support systems, and EVA systems, as well as a variety of space transportation-related technologies. In virtually all of these areas, advances are needed in miniaturization, sensors, lightweight materials, and information systems (including artificial intelligence). Table 3.3-2 provides a summary of the HEDS strategic technology needs associated with preparing for missions of human exploration.

Strategic Goal 3: Continuing to Open and Develop the Space Frontier

The HEDS Enterprise plans to advance human presence and activities in space, which includes flying the Space Shuttle program manifest safely, while aggressively pursuing needed systems improvements. The Enterprise will establish a permanent human presence in low-Earth orbit by transitioning from the Mir space station to the ISS. Also, HEDS will ensure the health, safety, and performance of space flight crews with cutting-edge medical practices using advanced technology. The Enterprise will pursue advanced concepts that make product breakthroughs in the human exploration and commercial development of space. Finally, HEDS will involve U.S. citizens, educators, and students in the space endeavor while promoting international cooperation.

Technology challenges that must be surmounted in achieving this strategic goal include enabling affordable human exploration and development of space by making transportation to, and through, space possible, at costs at least an order of magnitude lower than 1990 levels. (Technology development directed toward this challenge will also support HEDS Strategic Goal 2.) Another challenge will be to use the effects of the space environment to make possible new and better technologies, products and processes, and increased knowledge that may improve the quality of life on Earth. (Research and development in this area will support HEDS Strategic Goal 4.)

TABLE 3.3-2. SUMMARY OF STRATEGIC TECHNOLOGY REQUIREMENTS THAT ARE DRIVEN BY PREPARING TO CONDUCT HUMAN MISSIONS OF EXPLORATION

<i>Technology</i>	<i>Timeframe and Mission Class for Which TRL-5 Is Needed</i>		
	<i>Near-Term</i>	<i>Midterm</i>	<i>Far-Term</i>
Tools for Mission Design/Modeling	Robotic Mission Payloads	Near Space/Lunar	Deep Space/Planetary
Advanced Chemical Propulsion Systems	Robotic Mission Payloads	Near Space/Lunar	Deep Space/Planetary
Thermal Protection Systems	Robotic Mission Payloads	Near Space/Lunar	Deep Space/Planetary
Aeroassist Systems	Robotic Mission Payloads	Near Space/Lunar	Deep Space/Planetary
Miniaturized Systems/Sensors	Robotic Mission Payloads	Near Space/Lunar	Deep Space/Planetary
In Situ Resource Utilization	Robotic Mission Payloads	Near Space/Lunar	Deep Space/Planetary
Mini-Biosensor Systems (Crews)	—	ISS R&D Near Space	Deep Space/Planetary
Portable Clinical Lab Systems	—	ISS Near Space	Deep Space/Planetary
Advanced EVA Systems	—	Near Space/Lunar	Deep Space/Planetary
Planetary Surface Mobility Systems	—	Near Space/Lunar	Deep Space/Planetary
Advanced Robotic Systems	—	Near Space/Lunar	Deep Space/Planetary
Lightweight Structural Materials	—	Near Space/Lunar	Deep Space/Planetary
Radiation Shielding Materials/Systems	—	Near Space/Lunar	Deep Space/Planetary
Advanced Life Support Systems	—	Near Space/Lunar	Deep Space/Planetary
Advanced Power Systems—Solar	—	Near Space/Lunar	Deep Space/Planetary
Advanced Power Systems—Nuclear	—	Near Space/Lunar	Deep Space/Planetary
Cryogenic Fluids Storage/Transfer	—	Near Space/Lunar	Deep Space/Planetary
High-Performance Communications/Video	—	Near Space/Lunar	Deep Space/Planetary
Radiation Sensors and Solar Imaging	—	Near Space/Lunar	Deep Space/Planetary
Autonomous Operations and Health Maintenance	—	Near Space/Lunar	Deep Space/Planetary
Electric Propulsion Systems	—	—	Deep Space/Planetary
Nuclear Propulsion Systems	—	—	Deep Space/Planetary
Micro-Analytical Instruments	—	—	Deep Space/Planetary
High-Resolution Digital Medical Imaging/Storage	—	—	Deep Space/Planetary
Long-Shell-Life Medications/Storage	—	—	Deep Space/Planetary

To accomplish these objectives, a number of technologies are needed. Continuing improvements to the Space Shuttle system will depend on the steady maturation of technologies for a wide variety of specific applications. For example, technology advancements are needed in the areas of avionics, thermal protection systems (TPS), power generation, and various propulsion systems. Several operations-oriented technology development areas are also important to the Shuttle: EVA systems, cryogenic fluid storage and transfer, and communications systems.

A program of upgrades and systems enhancements for the ISS will be needed following the completion of ISS assembly. In the nearer term, some enhancements to support crew safety as well as possible scarring to support later enhancements will be needed. In these areas, the modularity of systems and technologies will be a key element of success. Some of the ISS-driven technologies needed in this thematic area include low-mass, long-lived energy storage systems; advanced power management and distribution; advanced thermal management capabilities; advanced reboost/propulsion capabilities; improved structural materials for Earth-orbiting structures; avionics; guidance, navigation, and control; software; and integrated system health monitoring. Enhancements in telerobotics operations and other telepresence technologies will be needed to enhance onboard research and free-flying platform operations and servicing and to reduce the costs related to crew training. In addition, advances in diverse operational and environmental sensors will be needed, taking advantage of developments in micro- and nanotechnology.

Finally, in the longer term, a number of technology advances are needed to support options for future ISS evolution to increase research productivity, drive down costs, and improve operability. Evolutionary systems options include improved habitation and interconnection nodes, advanced space power and thermal control systems, new logistics systems, enhanced accommodations for pressurized research, external research and free-flying platforms (ISS-based or visiting), and continuing improvements in operations. To enable these options, advances in a number of technologies are needed, including structural materials and concepts (such as for habitats), artificial intelligence (such as for operations), dexterous telerobotics, sensors (micro- and nanoscale), solar energy conversion systems, thermal control systems, power management and distribution, energy storage, and chemical processors. (Note that those technology development activities planned to be conducted on the ISS in support of other HEDS strategic themes—such as human exploration—are delineated in those sections of this document.) Table 3.3-3 provides a summary of HEDS strategic technology needs associated with continuing to open and develop the space frontier.

Strategic Goal 4: Aggressively Seeking Investment From the Private Sector

The HEDS Enterprise plans to promote private-sector investment in the human exploration and development of space. It will do this by various means, including facilitating the use of space for commercial products and services to increase private firm participation in space activities. In particular, HEDS plans to pursue privatizing Space Shuttle operations and to establish the feasibility of commercializing Shuttle and ISS operations. The Enterprise hopes to achieve early cost savings in space communications and to move toward the commercialization of NASA's space communications operations. In addition, HEDS will transfer knowledge and technologies and promote the creation of partnerships to improve health and enhance the quality of life.

Technology challenges include assuring that the Space Shuttle and ISS operate at continuously improving levels of safety and efficiency while supporting commercialization opportunities—for example, including advanced solar array power generation, power management, and integrated energy storage and attitude control flywheels. (Research and development in this vein would also support HEDS Strategic Goal 3.) In addition, the Enterprise must pursue technology that will increase the value of HEDS programs to more people in the areas of knowledge, space commerce, human experience, education, and technology. Technology development directed toward this challenge will also promote HEDS Strategic Goal 3.

TABLE 3.3-3. SUMMARY OF STRATEGIC TECHNOLOGY REQUIREMENTS THAT ARE DRIVEN BY CONTINUING TO OPEN AND DEVELOP THE SPACE FRONTIER

<i>Technology</i>	<i>Timeframe and Mission Class for Which TRI-5 Is Needed</i>		
	<i>Near-Term</i>	<i>Midterm</i>	<i>Far-Term</i>
Advanced Avionics	Space Shuttle Upgrades	Shuttle Upgrades	New Launch System
Thermal Protection Systems	Space Shuttle Upgrades	Shuttle Upgrades	New Launch System
Power Generation	Space Shuttle Upgrades	Shuttle Upgrades	New Launch System
Chemical Propulsion Systems	Space Shuttle Upgrades	Shuttle Upgrades	New Launch System
Advanced Structural Materials	Space Shuttle Upgrades	Shuttle New	New Launch System
Advanced Operational Sensors	Space Shuttle Upgrades	Shuttle Upgrades	New Launch System
Advanced Operational Sensors		ISS Upgrades	ISS Evolution
Actuators	Space Shuttle Upgrades	Shuttle Upgrades	New Launch System
Cryogenic Fluids Storage/Transfer	Space Shuttle Upgrades	Shuttle New	New Launch System
Communications Systems	Space Shuttle Upgrades	Shuttle Upgrades	New Launch System
Human Biosensors	ISS Enhancement	ISS Upgrades	—
Radiation Sensors/Systems	ISS Enhancement	ISS Upgrades	—
Artificial Intelligence (such as for Operations)	—	ISS Upgrades	ISS Evolution
Environmental Sensors	—	ISS Upgrades	ISS Evolution
Human Support Systems	—	ISS Upgrades	ISS Evolution/ Future Habs.
Advanced Power Systems (Solar, Power Mgmt./Distrib.)	—	ISS Upgrades	ISS Evolution
Advanced Power Systems	—	Future Habs.	Future Habs.
Telerobotics/Telepresence	—	ISS Upgrades	ISS Evolution
Mini-Biosensor Systems (Crews)	—	ISS Upgrades	ISS/Future Habs.
Portable Clinical Lab Systems	—	ISS Upgrades	ISS Evolution/ Future Habs.
Radiation Shielding Materials/Systems	—	Future Habs.	Future Habs.
Autonomous Operations and Health Maintenance	—	ISS Upgrades	ISS Evolution/ Future Habs.
Platform Structural Materials/Systems	—		ISS Evolution
Electric Propulsion Systems	—	—	New In-Space Systems

Many of the technologies needed to advance microgravity materials sciences could, when transferred, also play a strong role in future commercial microgravity processing research and development. This includes the areas cited previously, plus vibration isolation (both passive and active), high-temperature microgravity heat pipe technology, and developments across the board in instrumentation, measurement systems, and diagnostics for the microgravity sciences. These last areas include quasi-static accelerometers, noninvasive temperature sensors, gas velocity and species measurements, and particle tracking (including sprays), as well as safe mixing techniques for hazardous gases and fluids. Similarly, in microgravity life sciences, implantable miniaturized biotelemetry sensors and systems (along with associated signal processors and hardware) are required to enable the unrestrained monitoring of physiological parameters in rodents and small primates over periods of weeks. Similar sensors are needed for human crew monitoring.

Various communications technology advances are needed, including microminiaturized communications and navigation systems, autonomy in flight and ground operations, advanced data handling, and the achievement of interoperability among Government commercial systems. Specifically, high-bandwidth, multiple-beam links provided by communications satellites with onboard processing through the Global Information Infrastructure will play an important part in enabling commercial global telemedicine because of their unique ability to connect remote, mobile, and rural areas with urban medical care centers. Table 3.3-4 provides selected HEDS strategic technology needs associated with seeking investment from the private sector.

TABLE 3.3-4. SUMMARY OF STRATEGIC TECHNOLOGY REQUIREMENTS THAT ARE DRIVEN BY AGGRESSIVELY SEEKING INVESTMENT FROM THE PRIVATE SECTOR

<i>Technology</i>	<i>Timeframe and Mission Class for Which TRI-5 Is Needed</i>		
	<i>Near-Term</i>	<i>Midterm</i>	<i>Far-Term</i>
Miniaturized Comm./Navigation	Commercial ComSats	ComSats	ComSats
Autonomous Ground/Flight Operations	Commercial ComSats	ComSats	ComSats
Advanced Data Handling	Commercial ComSats	ComSats	ComSats
High-Bandwidth Satellite Communications		Commercial Telemedicine	Telemedicine
High-Temperature Microgravity Heat Pipes	—	Early Research	Commercial Furnaces
Advanced Photovoltaic Arrays	—	ISS Experiments	Commercial Platforms
Advanced Power Mgmt./Distribution	—	ISS Experiments	Commercial Platforms
Energy Storage (such as Flywheel Based)	—	ISS Experiments	Commercial Platforms
Mini-Biosensor Systems (Animals)	—	ISS Experiments	ISS Experiments
Artificial Intelligence (e.g. for Operations)	—	ISS Experiments	ISS Experiments

3.4 Aero-Space Technology Enterprise

The annual Aeronautics and Space Reports of the President and the National Space Policy outline U.S. policies and actions needed for continued national leadership in aeronautics and space. NASA has formulated these policies and actions into one of the fundamental questions of science and technology:

How can we enable revolutionary technological advances to provide air and space travel for anyone, anytime, anywhere more safely, more affordable, and with less impact on the environment and improve business opportunities and global security?

Providing revolutionary new tools and technology advancements is the response of NASA's Aero-Space Technology Enterprise to our Nation's needs. NASA framed its response into three strategic goal areas, which it calls the "Three Pillars" of the Enterprise (see Figure 3.4-1).

Throughout the strategic goal areas are "Enabling Technology Objectives," which are challenges stated in terms of a final outcome—the anticipated benefit of NASA-developed technology once it has been incorporated by industry into its products. These objectives have been developed in collaboration with our industry partners, the Department of Defense, the Federal Aviation Administration, and academia. They require taking risks and will stretch the boundaries of our knowledge and capabilities, but the impact of NASA's research on our national air transportation system, our national security, the environment, and our economy demonstrates a clear Government role in support of the public good.

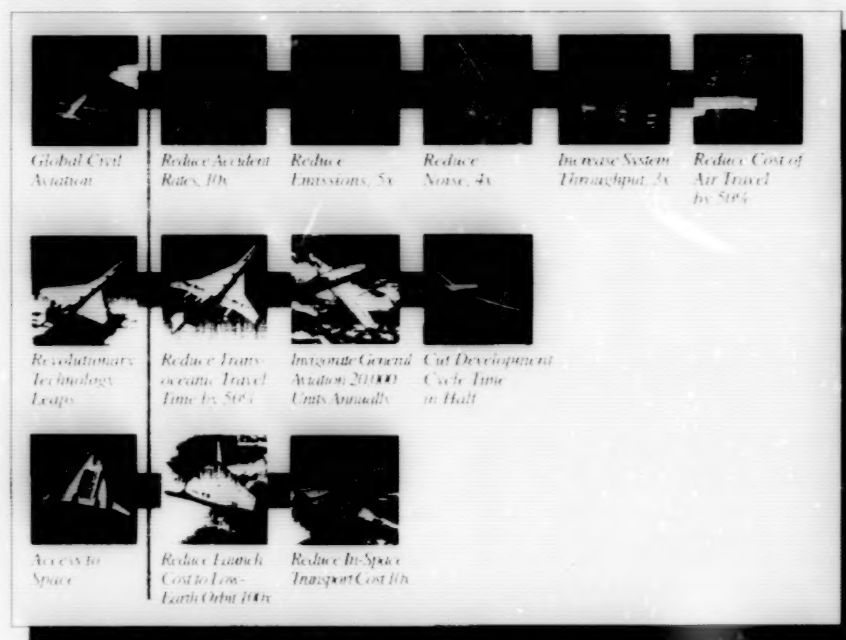


FIGURE 3.4-1. THREE PILLARS/10 ENABLING TECHNOLOGY OBJECTIVES

The (then) Office of Aeronautics conducted a scenario-based strategic planning process to identify the most significant long-term needs of the Enterprise—the Enabling Technology Objectives—as well as the technology needs for satisfying those goals. Instead of projecting the most probable future, this process consisted of projecting a set of alternative futures that were intended to envelop the possible alternatives. In this way, the most pervasive needs and the most robust technological opportunities could be identified. The resulting technological objectives for the Three Pillars are listed in Table 3.4-1.

Global Civil Aviation (Pillar One)

Transportation is an enormous and critical element of the national economy. Today, air travel (civil aviation) provides the backbone for long-distance and global transportation, as well as the basis for global economic and cultural exchange and integration. The United States has traditionally led this large and growing market in which projected growth is expected to approach a tripling of operations over the next 20 years. Moreover, an examination of various alternative futures suggests that there is also the potential for greater dispersion of operations, very high value for flexible, ultra-reliable operations, and increasing utilization of aircraft with unique operational characteristics.

These trends stress the need to address the fundamental, systemic issues for the aviation system to ensure the continued growth and development appropriate to the needs of the national and global economies. These systemic issues include safety, capacity, environmental compatibility, and affordability. These issues cut across markets, including large subsonic civil transports, air cargo, commuter and general aviation, and rotorcraft. To ensure that these systemic issues do not become constraints, dramatic improvements must be pursued.

**TABLE 3.4-1. THREE PILLARS OF THE AERO-SPACE TECHNOLOGY ENTERPRISE
 AND THE ENABLING TECHNOLOGY OBJECTIVES**

Pillar One: Global Civil Aviation	<ol style="list-style-type: none"> 1. Reduce the aircraft accident rate by a factor of five within 10 years, and by a factor of 10 within 25 years 2. Reduce emissions of future aircraft by a factor of three within 10 years, and by a factor of five within 25 years 3. Reduce the perceived noise levels of future aircraft by a factor of two from today's subsonic aircraft within 10 years, and by a factor of four within 25 years 4. While maintaining safety, triple the aviation system throughput, in all weather conditions, within 10 years 5. Reduce the cost of air travel by 25 percent within 10 years, and by 50 percent within 25 years
Pillar Two: Revolutionary Technology Leaps	<ol style="list-style-type: none"> 6. Reduce the travel time to the Far East and Europe by 50 percent within 25 years, and do so at today's subsonic ticket prices 7. Invigorate the general aviation industry, delivering 10,000 aircraft annually within 10 years, and 20,000 aircraft annually within 25 years 8. Provide next-generation design tools and experimental aircraft to increase design confidence, and cut the development cycle time for aircraft in half
Pillar Three: Access to Space	<ol style="list-style-type: none"> 9. Reduce the payload cost to low-Earth orbit by an order of magnitude, from \$10,000 to \$1,000 per pound, within 10 years, and by an additional order of magnitude, from \$1,000 to \$100 per pound, within 25 years 10. Reduce the cost of interorbital transfer by an order of magnitude within 15 years, and reduce travel time for planetary missions by a factor of two within 15 years, and by an order of magnitude within 25 years

Efficient transportation is essential for a productive economy. To enhance our Nation's economic health and the welfare of the traveling public, NASA must continue to provide the high-risk, high-payoff technology advances that will enable safer, cleaner, quieter, and more affordable air travel and that provide even greater flexibility, convenience, and mobility in our air transportation system. Developing the enabling technologies needed to meet these objectives is the challenge facing the Aero-Space Technology Enterprise.

Enabling Technology Objective 1 (Reduce the Accident Rate, 10x). Our global society is highly dependent on air transportation. Great strides have been made over the last 40 years to make flying the safest of all the major modes of transportation. However, even today's low accident rate is not good enough. If air traffic triples as predicted, this rate will be totally unacceptable. The impact on domestic and international travel will have economic consequences well beyond the American transportation sector. Dramatic steps through joint Federal Aviation Administration, Department of Defense, and NASA research will assure unquestioned safety for the traveling public. Because of the enormous public benefit and its fundamental importance to the growth of air travel, the Aero-Space Technology Enterprise will implement a broad-based and sustained investment to develop aviation safety technologies. The technology challenges to reducing the accident rate are in three areas: accident prevention (systemwide, single aircraft, and weather), accident mitigation, and aviation system monitoring and modeling. Technology needs within these areas are listed in Table 3.4-2.

TABLE 3.4-2. TECHNOLOGY CHALLENGES TO REDUCING THE AIRCRAFT ACCIDENT RATE

Systemwide Accident Prevention	<ul style="list-style-type: none"> • Human error modeling to develop error-mitigating approaches for human-system operations • More effective training procedures and aids • Tools for increased maintenance effectiveness
Single Aircraft Accident Prevention	<ul style="list-style-type: none"> • Health management and flight critical system design • Precision approach and landing information • Control upset management • Engine containment
Weather Accident Prevention	<ul style="list-style-type: none"> • Enhanced situational awareness in reduced visibility • High-fidelity, timely, intuitive graphical information for the flight deck and air traffic control • Tools for detecting and mitigating weather hazards
Accident Mitigation	<ul style="list-style-type: none"> • Prediction methodologies for crashworthy designs • Detection and suppression of inflight fires • Crash-resistant fuel systems • Low-heat-release materials and fire-safe fuels
Aviation System Monitoring and Modeling	<ul style="list-style-type: none"> • Modeling and simulation • Systemwide incident monitoring tools • International taxonomies to ensure seamless user-friendly data bases • Analytical tools to identify causal factors, accident precursors, and off-nominal conditions

Enabling Technology Objective 2 (Reduce Emissions, 5x). In its 1995 report titled "Goals for a National Partnership in Aeronautics Research and Technology," the White House National Science and Technology Council noted: "Environmental issues are likely to impose the fundamental limi-

tation on air transportation growth in the 21st century." Although aircraft produce only a small fraction of the world's air pollution compared to other sources, it is in the best interest of our Nation to protect the environment. The United States must demonstrate leadership in setting and meeting challenging environmental goals for aviation. We believe it is possible to significantly reduce aircraft emissions that contribute to global warming, degradation of local air quality, and ozone depletion, even as travel volume increases. In collaboration with carriers, manufacturers, academia, and other Government agencies, NASA will develop robust technology options with the objective that environmental issues do not constrain the growth of air transportation. Key challenges and potential technology areas are listed in Table 3.4-3.

TABLE 3.4-3. KEY ENVIRONMENTAL CHALLENGES AND POTENTIAL TECHNOLOGY AREAS

Continuing Improvement in Gas Turbine-Powered Aircraft	<ul style="list-style-type: none"> • Lightweight, durable wing and fuselage materials and monolithic structures • Improved aerodynamic design • Laminar flow control • Slatless/flapless airfoils • Revolutionary aircraft designs • Designer materials • Electric airplanes
Alternate Fuels, Propulsion Systems, and Aircraft Concepts	<ul style="list-style-type: none"> • Lightweight, high-temperature materials for ultrahigh-bypass ratio engines • Nontraditional propulsion/airframe integration • Intelligent controls • Improved injectors and liners • Improved characterization of emissions • Smart adaptive engines • Noncarbon based fuels • Noncombustion propulsion systems
Advanced Ground and Flight Operations	<ul style="list-style-type: none"> • Modeling and assessment • Improved ground operations • Improved flight operations • Hydrogen handling

Enabling Technology Objective 3 (Reduce Noise, 4x). Aircraft noise is the other area in which future environmental standards will require innovation. Previous NASA noise reduction research is now embodied in new aircraft entering the fleet and in modifications to existing aircraft. As increases in noise constraints, such as noise abatement procedures, curfews, and surcharges, have caused the number of impacted airports worldwide to grow, can we continue to meet international regulations and local rules while maintaining and improving the competitiveness of air transportation? Can we go further and create aircraft that are so quiet that the predominant noise at airports comes from cars and buses? Along the modeling noise and its human impact, key technical challenges include mitigation through improvements listed in Table 3.4-4.

TABLE 3.4-4. KEY TECHNICAL CHALLENGES FOR NOISE MODELING AND ITS HUMAN IMPACT

Modeling and System Integration	<ul style="list-style-type: none"> • Realistic integrated noise model • First principle system noise prediction • Real-time noise models • Noise minimization techniques • Global population and land-use impact
Quiet Engine Systems	<ul style="list-style-type: none"> • Broadband noise reduction techniques • Fan, core, and jet reduction techniques • Flow management • Propellers and rotor blade designs and materials • Engine active noise control • Computational aero-acoustics
Quiet Airframe Systems	<ul style="list-style-type: none"> • Turbulence and separation control • Trailing-edge noise control • Structures and aerodynamic design • Propulsion airframe integration • Airframe active noise control • Computational aero-acoustics
Airspace Operations to Minimize Noise in Surrounding Communities	<ul style="list-style-type: none"> • High-capacity noise minimization • Operation compression • Reduced automation barriers • Real-time noise management • Noise-sensitive air traffic management systems

Enabling Technology Objective 4 (Increase the System Throughput, 3x). An efficient and effective air traffic management system is vital to the U.S. transportation infrastructure. U.S. airlines estimate that limitations in the current system cost \$3.5 billion annually in excess fuel burn and additional operational costs and thousands of hours of delays to the flying public. Current Federal Aviation Administration standards require a reduction in terminal operations during instrument-weather conditions at many airports, causing delays and reducing airport productivity, which increases the cost of operating aircraft. More efficient routing, scheduling, and sequencing of aircraft in all weather conditions are critical to meeting capacity demands. The long-term benefits are reduced operational costs and a larger aviation market, both nationally and in countries where air traffic efficiency is limited.

Another part of the solution to capacity demands is to off-load the major airports by developing short-haul routes among the 5,200 public-use airports available throughout the country. These short-haul routes could be served by a new fleet of U.S.-manufactured general aviation and civil tiltrotor aircraft.

The technology needs to enable productivity of the airport terminal area in instrument-weather conditions to safely match that of clear-weather (or visual) conditions should include procedures to safely reduce aircraft spacing in the terminal area, enhanced air traffic management, and reduce

controller workload. With improved wake vortex knowledge, "dynamic spacing" between pairs of aircraft types in the landing sequence for a given airport runway system would be possible.

NASA's effort relating to the civil tiltrotor emphasizes the development of technology for civil tiltrotor configurations and focuses on the need for noise reduction, cockpit technology for safe, efficient terminal area operations, and contingency power. To achieve acceptable levels of external noise in the terminal area, tiltrotor noise must be reduced by 6 decibels A-weighted (dBA) over current technology. Complex flight profiles involving steep approach angles and multisegmented approach paths would enable an additional 6-dBA reduction. For these approaches to be safely flown under all weather conditions, integrated and automated control laws and displays are needed. The capability to recover from an engine failure requires the development of contingency power options that can provide single-engine hover capability without excessive engine weight. Key technical challenges for increased airport terminal area productivity are listed in Table 3.4-5.

TABLE 3.4-5. KEY TECHNOLOGY CHALLENGES FOR INCREASED AIRPORT PRODUCTIVITY

Safe, Efficient Traffic Management	<ul style="list-style-type: none"> • Trajectory modeling and prediction • Conflict prediction and resolution • Error-tolerant human factors • Situation-adaptive logic • Aircraft autonomy • Coordinated multi-airplane operations • Air-ground integration
Full-Capacity All-Weather Operations	<ul style="list-style-type: none"> • Vortex sensing and modeling • Advanced display and navigation aids • Distributed decision-making • Air-ground integration • Automated multiple coupled landing • All-hazard modeling and detection/alerting • Icing prediction and protection
Robust Distributed Information Systems	<ul style="list-style-type: none"> • Information and software integrity and security • Data mining • Distributed computing • High-bandwidth networking • Satellite communications
Accurate Systems Analysis and Assessment Tools	<ul style="list-style-type: none"> • Airspace modeling • Noise and emissions modeling • Human performance modeling • Decision support tool modeling
Nonrunway Operations	<ul style="list-style-type: none"> • Simultaneous noninterference operations • Digital Global Positioning System and operations procedures • Human-centered cockpit • Adverse weather systems • Steep-descent operations

Enabling Technology Objective 5 (Reduce the Cost of Air Travel by 50%). Reducing the cost of air travel is aimed at a radical improvement in mobility for the traveling public by making commercial air transportation more affordable, easier to use, and more accessible. The key to attaining this goal is the introduction of breakthrough aircraft system technologies and paradigm shifts in aviation system operations that produce significant improvements over evolutionary trends in reducing the cost of air travel. Revolutionary technologies provide dramatic improvements in affordability and simplicity of air travel, resulting in dramatic reductions in ticket price and reduced intra-airport travel. Productivity paradigm shifts provide increased accessibility and availability by creating a revolutionary intermodal transportation system to radically alter portal-to-portal process, 24-hour operations with significantly increased flight segment options and the elimination of cancellation because of maintenance delays. Reducing the cost of air travel is the key to integrating the technology developments that enable the first four objectives of the Global Civil Aviation Pillar. Table 3.4-6 is a list of the key technical challenges to reducing the cost of air travel.

TABLE 3.4-6. KEY TECHNICAL CHALLENGES TO REDUCING THE COST OF AIR TRAVEL.

Revolutionary Configurations	<ul style="list-style-type: none"> • Lightweight, low-cost nontraditional structures • Simple, efficient engines • Lightweight, affordable propulsion components • Lightweight, low-cost subsystems • Improved aerodynamic efficiency • Design process integration tools
Productivity	<ul style="list-style-type: none"> • Durable, smart structures • Low-maintenance, fault-tolerant engines • Highly reliable subsystems • Simple, ultralow-noise airframes • Quiet engines • Airport/aircraft life-cycle utilization optimization processes

Revolutionary Technology Leaps (Pillar Two)

Enabling the future of air transportation goes beyond addressing the critical systemic issues of global civil aviation. Enabling new markets and new ways of doing business will once again push the frontiers of aviation to the benefit of our Nation and the world. While the range of possible avenues is vast, the Aero-Space Technology Enterprise, working in cooperation with its partners, is focused on three critical areas that will expand the horizons for all users of air transportation: eliminate the barriers to affordable supersonic travel, expand the benefit and utilization of general aviation in tomorrow's transportation system, and significantly accelerate the application of technology advances in air and space transportation systems.

Enabling Technology Objective 6 (Reduce Transoceanic Travel Time by 50%). The High Speed Civil Transport (HSCT) is envisioned to be our next-generation supersonic transport. This

vehicle would fly at Mach 2.4 and have sufficient range to reach Far East destinations. The key to industry's decision on whether to proceed with product launch, however, is assurance that HSCT operations will meet environmental standards for noise and emissions. Likewise, the HSCT must be economically viable. A ticket price of less than 20-percent surcharge over today's subsonic ticket price is envisioned for a first-generation HSCT, assuming existing technologies are matured. The benefits to the United States resulting from the development of an HSCT include providing a commercial transport that cuts passenger travel time in half and improves airline efficiency. Also, the production of an HSCT could potentially create 140,000 new jobs and result in an increase in balance of trade on the order of \$400 billion.

Achieving the economic goal of meeting today's subsonic ticket prices without compromising continually more stringent environmental standards will require the maturation of technologies beyond those in place today. The primary technologies required to reach the goal are listed in Table 3.4-7.

TABLE 3.4-7. PRIMARY TECHNOLOGIES REQUIRED TO REDUCE TRAVEL TIME

Economic Viability	<ul style="list-style-type: none"> • Lightweight, high-temperature airframe materials and structures • Simple, efficient engines • Lightweight, affordable propulsion components • Lightweight, low-cost subsystems • Improved aerodynamic efficiency • Design process integration tools
Environmental Compatibility	<ul style="list-style-type: none"> • Durable, smart structures • Low-maintenance, fault tolerant engines • Highly reliable subsystems • Simple, ultralow-noise airframes • Quiet engines • Airport/aircraft life-cycle utilization optimization processes

Enabling Technology Objective 7 (Invigorate General Aviation 20,000 Units Annually). General aviation has a long history in the United States and has expanded globally. However, while business jets continued to advance, the personal aircraft segment of general aviation stagnated in the late 1970's as complexity, cost, and liability issues constrained expansion. Fortunately, critical tort reform in 1994 has opened the door for the renewal of general aviation. Moreover, the development and application of new technologies can dramatically improve the ease of use, reliability, and cost of general aviation vehicles. New concepts are being explored that can safely and efficiently expand the use of general aviation within the Nation's transportation system, with the possibility of creating new social and economic opportunities for U.S. citizens. In meeting the goal, small aircraft transportation system technologies could dramatically stimulate an expanded mobility by serving 25 percent of suburban, exurban, rural, and remote communities in 10 years, and 100 percent of those communities in 25 years. The final objective is to provide high-speed, intermodal personal and business transportation mobility to a more diverse population of travelers. The technologies needed to meet the general aviation goal are listed in Table 3.4-8.

TABLE 3.4-8. TECHNOLOGIES NEEDED TO MEET THE GENERAL AVIATION OBJECTIVE

National Airspace System Infrastructure Integration	<ul style="list-style-type: none"> • Low-cost Local Area Augmentation System • Flight Information Service datalink in 100 percent of the States • Satellite-based communications, navigation, and surveillance • Automatic Dependent Surveillance-Broadcast-based operations at nontowered, nonradar airports
Affordable Propulsion Systems	<ul style="list-style-type: none"> • Low-cost turbines • Low-cost compressors • Nonhydrocarbon propulsion • Quiet propulsion systems
Single-Crew Flight Deck Systems and Operations	<ul style="list-style-type: none"> • Decoupled controls • Enveloped protection • Improved ride quality • Certifiable software development tools for displays applications • Affordable heads-up displays • Synthetic vision and displayless cockpits • Embedded, onboard training • Reduced time and cost of training • VHF Data Link Mode 3 data radios
Affordable Airframes	<ul style="list-style-type: none"> • Low-cost, lightweight airframe materials and structures • Automotive synergies • Robust manufacturing • Optimized ice, lightning, and crash protection

Enabling Technology Objective 8 (Cut the Development Cycle Time in Half). This area of revolutionary advancement will dramatically affect the way we do business. Its impact will be felt across each of the three Revolutionary Technology Leaps Pillar goals, contributing to every enabling technology goal. If we are to achieve the pillar enabling technology goals, we must accelerate the introduction of new technologies into air and space transportation systems. This implies faster and cost-efficient design and development cycles, leading to more rapid and frequent introductions of new systems.

Revolutionary design tools will be developed to enable new approaches to the development process and environment. The tools must accommodate geographic distribution of engineering and design teams, integrate many disciplines and issues, and provide greater information earlier in the development process. The risks, costs, and benefits of new technologies must be readily incorporated and analyzed.

History has shown that it has taken years—even a decade or two—to bring a new flight vehicle from the concept stage through development, design, manufacturing, and certification of the new

aircraft. Such long processes require design choices and "freezes" so early in the cycle that new aircraft can neither take advantage of rapidly developing technologies nor respond to rapidly evolving societal expectations or regulations. NASA is joining with other Federal agencies, industry, and academia to bring their combined world-class expertise and capabilities to dramatically and drastically cut this design cycle time and increase early design confidence. The primary technology challenges for next-generation design tools are listed in Table 3.4-9.

TABLE 3.4-9. PRIMARY TECHNOLOGY CHALLENGES FOR NEXT GENERATION DESIGN TOOLS

Validated Rapid Modeling	<ul style="list-style-type: none"> • Rapid, physics-based analysis with modular capabilities (such as unsteady phenomena, materials properties, manufacturing processes, and combustion) • Life-cycle master models • Cost models • Variable fidelity, fully scalable time capability • Radical concepts for ultrafast computing
Revolutionary Validation Processes	<ul style="list-style-type: none"> • Low-cost, high-accuracy sensing • Nonintrusive measurement • Knowledge-based data analysis • Remote operation of test environment • Intelligent, real-time data comparison • Automated, intelligent test generation systems • Rapid prototype-to-test capability • Integrated design systems and test environment
Knowledge Management	<ul style="list-style-type: none"> • Rapid, robust visualization tools • High-capacity data compression and storage • Data fusion • Virtual tool libraries and data bases • Intelligent interfaces • Automated process management/guidance • Knowledge capture • Data mining • Real-time correlation, analysis, and control
Distributed Collaborative Environment	<ul style="list-style-type: none"> • Standard tools and practices • Common interface, exchange, and translators • High-capacity secure networks • Rapid information exchange • Telepresence • Full sensory immersion technology
Life-Cycle and Process Integration	<ul style="list-style-type: none"> • Baseline life-cycle analysis • System integration • Rapid, high-fidelity hardware and software testing • Flexible, seamless system architecture • Intelligent agent-based integration of tools • Automated resource management tools

Experimental flight vehicles are invaluable tools for exploring new concepts and for complementing and strengthening laboratory research. The very demanding environment of flight can test innovative, high-risk concepts and accelerate their development into applications. The Aero-Space Technology Enterprise will utilize advanced concepts and experimental flight research as an integral part of achieving the pillar's enabling technology goals.

Advanced concepts will exploit the unique value of experimental aircraft for exploring new concepts, supporting Aero-Space Technology Enterprise goals through technology validation, and complementing and strengthening laboratory research. Through the use of industry-Government cooperative agreements, NASA intends to leverage diverse technology developments to increase and improve the use of experimental aircraft as both a research tool and a flight validation means.

Experimental aircraft (both piloted and unpiloted) will be used to test innovative, high-risk concepts, accelerating the implementation of aircraft developments through reductions in the design cycle and the certification process. The primary technology challenges for advanced concepts are listed in Table 3.4-10.

TABLE 3.4-10. TECHNOLOGY CHALLENGES FOR ADVANCED CONCEPTS

Advanced Concepts	<ul style="list-style-type: none"> • Precise and rigorous modeling and scaling techniques • Revolutionary departures from traditional design concepts • Rapid prototyping technology to enable affordable and timely experimental aircraft • Early identification of certification issues that can be addressed through flight research • The amelioration of flight test data acquisition and reduction systems and subsequent implementation into the aircraft design cycle
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Access to Space (Pillar Three)

For more than three decades, the United States has led the world in the exploration and use of space. Space transportation systems, such as the Space Shuttle and commercial Expendable Launch Vehicles, provide the means by which we can live and operate in space and are the enabling mechanism for achieving NASA's mission. While these systems provide the most affordable and reliable launch capability available today, the relative high cost, low reliability, and limited capability of existing systems severely limit achievements in space science, exploration, and commercial development. Our understanding of the universe is restricted, and many valid scientific questions go unanswered as missions and experiments remain unplanned and unmanifested.

In the United States, the cost of space access is roughly \$10,000 per pound of payload delivered to low-Earth orbit. Over the last 25 years, we have developed only one major new launch system and one rocket engine—the Space Shuttle and the Space Shuttle Main Engine. In the same timeframe, other nations have developed more than 25 rocket engines and many more launch vehicles. Our launchers, once preeminent, now supply less than 40 percent of the worldwide

commercial market in terms of dollars. In the world's rapidly expanding launch business, the United States must continue to lower launch costs to maintain its market share. Within NASA, the Space Shuttle expends nearly 25 percent of our annual operating budget and is the primary area that must be addressed to expand Aero-Space Technology Enterprise investments in today's tight budget environment.

In the coming decades, NASA envisions the space frontier as a busy crossroads of U.S.-led international science, research, commerce, and exploration. Our efforts have already yielded vast treasures of scientific knowledge, new commercial enterprises, life-enhancing applications for use on Earth, and fantastic celestial discoveries. Significant improvements in the cost and reliability of space transportation must be achieved to enable NASA, and the Nation, to conduct faster, better, and cheaper programs in research, science, and exploration, while enabling our commercial U.S. launch vehicle industry to regain its position in the global market. Low-cost space access is the key to realizing this vision, to satisfying NASA's long-term strategic plans, and to enabling the U.S. launch vehicle industry to compete in a global market. Enabling the full commercial potential of space and the expansion of space research and exploration will require truly affordable and reliable access to space. To respond to this challenge, the Advanced Space Transportation program is structured around two enabling technology objectives.

Enabling Technology Objective 9 (Reduce the Payload Cost to Low-Earth Orbit 100x by 2022)

Near-Term Objective. The Reusable Launch Vehicle (RLV) program is structured to respond to the industry's need to reduce or eliminate the technology risk of building a new system. The centerpiece of the program is a series of flight demonstrators (X-vehicles) that serve to force technologies from the laboratory into real-world operating environments. This approach will provide the level of technology maturity through demonstrated system concepts required to retire the unacceptable development risk. NASA has incorporated this commercial focus from early technology planning through program implementation and evaluation. Innovative partnerships have been formed that strengthen the alliance between industry and Government, thus eliminating unfocused technology and assuring convergence between commercial capabilities and national needs. The primary technology challenges for the RLV program are listed in Table 3.4-11.

Twenty-Five-Year Objective. Building on the earlier aeronautics research and technology programs, the Advanced Space Transportation program is focused on highly reusable vehicle systems and propulsion systems investments beyond the current RLV focus that have the potential to reduce dramatically vehicle life-cycle costs. Extensive planning has been undertaken by Integrated Planning Teams, composed of NASA Center personnel, the Department of Defense, and industry representatives, to develop core technology advancement plans for vehicle structures, thermal protection systems, propulsion systems, and avionics/operators. An intercenter process has been put in place to prioritize advanced reusable technology investments based on their system payoff in terms of improvements in mission capability, cost, reliability, operability, responsiveness, and safety. In a recently completed study by NASA, the criteria shown in Table 3.4-12 were established as guidelines for meeting this goal.

TABLE 3.4-11. TECHNOLOGY CHALLENGES FOR THE RLV PROGRAM

Reusable Launch Vehicles	<ul style="list-style-type: none"> • Highly reusable technologies that are mass-fraction scalable to a single-stage-to-orbit rocket launch system, including the primary structure, cryogenic tank, insulation, and thermal protection system • Robust subsystems that will enable vehicles with at least a 100-mission life, 20 flights between depot maintenance, and an order-of-magnitude reduction in processing labor hours compared to the Shuttle • Durable, lightweight thermal protection systems that will be easy to inspect, maintain, and repair • Main propulsion system with thrust-to-weight of at least 80, with robust subsystems that will enable at least a 50-percent reduction in engine inspection time between flights as compared to the Shuttle • System reliability of at least 0.995 for mission success and 0.999 for vehicle/payload recovery • Design, development, test, and evaluation costs and production costs less than one-third that of the Shuttle
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TABLE 3.4-12. HIGHLY REUSABLE SPACE TRANSPORTATION (HRST) SYSTEM CRITICAL TECHNOLOGY REQUIREMENTS

<i>Criteria</i>	<i>Requirements</i>
Payload Range	20,000-40,000 pounds
Propellant Mass Fraction	Less than 80 percent
Payload Mass Fraction	Greater than 5 percent (allowing for increased robustness)
Vehicle Life	1,000-2,000 flights per airframe
Engine Life	Greater than 200 flights per engine with 50-60 flights between major overhaul
Propulsion System	ISP effective greater than 550
Operability	Less than 1-week turnaround between flights
Reliability	0.9999 for engine /0.9995 for vehicle
Personnel	Less than 200 people in recurring operations
Production Costs	\$5,000-\$10,000 per pound of vehicle
Development Costs	\$5 billion to \$10 billion (industry-Government shared)

Technologies that were found to have the largest potential for meeting one or more of these guidelines were given high priority in the planning process. The initial focus for advanced reusable technologies has been on air-breathing rocket-based combined cycles because of an air-breathing rocket's potential to substantially increase engine performance over the pure rocket system. Future technology investments will focus on advanced materials to reduce weight and improve engine life, advanced nozzles to improve performance, and turbomachinery technologies to improve reliability and engine life. The aim will be to mature technologies through ground testing and analyses to the point where they can be considered for flight evaluation.

Enabling Technology Objective 10 (Reduce the In-Space Transportation Cost 10x by 2012)

Earth Orbit. Most space missions will require placement of payloads into orbits significantly higher than low-Earth orbit. Over the next 10 years, more than 30 percent of the planned expendable launches will be to geosynchronous orbit. Because approximately 60 to 70 percent of the weight of a typical geosynchronous satellite and its upper stage is the propulsion system (including propellant), significant leverage can be obtained through performance improvements in the in-space propulsion area. Performance improvements can be used to either increase payload capability or to step down to a smaller, less costly launch vehicle. For RLV, reduced requirements for upper stages will provide significant leverage for increasing delivered spacecraft weights to operational orbits. Significant opportunities exist to improve in-space propulsion performance capability either as part of a separate upper stage or as part of the spacecraft onboard integral propulsion system, which is used for transfer to the initial operational orbit, for orbit Delta-V maintenance, and for final end-of-mission disposal. Significant investments have been made by Government and industry in evolving solid, liquid-storable, cryogenic, and electrochemical systems. The primary focus is on advanced technologies to reduce system weight and improve performance. The Government-industry investments are jointly coordinated through the Integrated High Payoff Rocket Propulsion Technology Initiative.

Propulsion systems based on energy sources external to the spacecraft hold promise for significant reductions in propulsion system weight. Near-term technologies based on solar electrostatic technology (1 to 4 kilowatts) are currently being considered for spacecraft Delta-V maintenance and disposal. Power levels on the order of 20 kilowatts will be required in combination with chemical propulsion for orbit raising and orbit insertion. The limiting factor to the extent of electric propulsion utilization is the amount of time the spacecraft operators will be willing to wait for final insertion and initiation of operations. Nominal trip times from 60 to 120 days seem to be feasible to commercial operators and could result in improvements in delivered spacecraft weight by more than 20 percent. The development and demonstration of electrostatic (Hall-effect) propulsion for this application is a top priority by both NASA and Department of Defense space transfer technology programs. Another promising technology is solar-thermal propulsion if specific impulses on the order of 1,000 seconds can be obtained in an operational system; however, significant technology advancements will be required. Electrodynamic tether propulsion also shows promise for propellantless Earth orbit transfer. The technology for tethers is relatively mature, and a flight demonstration is planned to validate a small deployer system to deorbit an upper stage within days instead of the months now required.

In the long term, reusable orbit transfer vehicles, either space based or returned to ground for turnaround, are key to achieving an order-of-magnitude reduction in orbit transfer costs.

Planetary Science and Exploration. The SSE Enterprise is focused on frequent, ambitious missions that can be performed on smaller spacecraft without sacrificing capability so that more ambitious missions can be launched with smaller launch vehicles. Advances in avionics and sophisticated structural design have helped reduce the mass of spacecraft; commensurate reductions in the mass of propulsion systems and increases in the capability of those systems are necessary if the space science vision is to be realized. Innovative approaches to reduce mission costs substantially will be needed to realize eventual human exploration and intensive scientific

research on other planets. Transportation, which represents a substantial portion of overall mission costs, will benefit significantly from reduced travel time and propulsion system mass.

Interplanetary Transfer. Future space science missions to the outer planets, to Mercury, and to the Sun all require significantly greater Delta-V than that which has characterized past missions. This realization and the need to fit within the capability of smaller launch vehicles led to the current NASA Solar Technology Application Readiness (NSTAR) program to validate ion propulsion technology on the Deep Space 1 spacecraft launched in October 1998, which at a maximum power of 2.5 kilowatts is sized appropriately for spacecraft of the Discovery class. Future smaller spacecraft with limited power capability will require electric propulsion systems whose maximum power capability is 1 kilowatt or less. Furthermore, the use of very small spacecraft make the use of solar sail propulsion very attractive for high total Delta-V missions that would otherwise require large amounts of propellant over mission life. High-power electric propulsion (100-kilowatt level and higher) is a potential option for a manned mission to Mars or rendezvous missions with the outer planets. Other options may include the need for nuclear propulsion systems.

Planetary Orbit Insertion. Future space science missions include a significant number of planetary orbiters, such as the Europa Orbiter mission planned for 2003. The mass imperative imposed by decreasing spacecraft size and smaller launch vehicles requires that the dry mass of the orbit insertion propulsion systems for these spacecraft be reduced by a factor of two relative to current technology. Aerocapture/aerobraking technologies can be used to reduce propellant requirements for planets with a suitable atmosphere and for return missions to Earth.

Planetary Return. The Mars Sample Return mission planned for 2005 cannot be accomplished with the baselined Delta III launch vehicle using today's state of the art in propulsion. A lightweight, 600-pound rocket engine, a factor-of-two reduction in the dry mass of the propulsion system, and propellant compatibility with the thermal environment of the Martian surface are all requirements that cannot be met with today's technological capability. The use of in situ resource products for propellants could play a major role in reducing mission costs for future planetary exploration missions.

Advanced Propulsion Concepts. Propulsion is a technology discipline critical to NASA's long-term future. Breakthrough technological approaches may be necessary for Earth-to-orbit vehicles to achieve several orders-of-magnitude reduction in launch costs. Space exploration will continue to become more ambitious. Performing an interstellar mission is an enormous challenge for space propulsion. Sending a spacecraft to our nearest neighboring star within one's career time span is a very difficult task, requiring the spacecraft to accelerate to a significant fraction of the speed of light. A large number of science objectives may be accomplished at interstellar precursor distances; exploration of the Oort Cloud and the Kuiper Belt, sampling of the interstellar medium, and refined stellar parallax observations are some examples of ambitious intermediate goals. Routine human space travel within our solar system would also benefit from high-power density propulsion technologies. The primary technology challenge is dramatic improvement in propulsion performance, including advanced cycles, new onboard energy sources, offboard energy sources, and breakthrough physics. A list of the technology challenges for improved propulsion performance appears in Table 3.4-13.

TABLE 3.4-13. KEY TECHNOLOGY CHALLENGES FOR INCREASED AIRPORT PRODUCTIVITY

Reusability	<ul style="list-style-type: none"> • Long-life, high-power electric propulsion systems (Hall-effect thrusters) combined with high-power solar power system enabling direct power conversion • Precision aeroassist/aerobraking for the return trip to Earth or Earth orbit • Lightweight, reusable thermal protection systems for Earth return
In-Space Operations	<ul style="list-style-type: none"> • Reusable cryogenic engines • Long-term cryogenic propellant storage • Management and autonomous rendezvous necessary for any space-based option
Space Science and Exploration	<ul style="list-style-type: none"> • Reduced propulsion system dry mass for both electric and chemical systems by up to 50 percent • Improved ion propulsion life, reliability, and xenon throughput by greater than 100 percent • Lightweight, more efficient solar arrays • Solar sails for non-Keplerian orbits and high total Delta-V missions • Electric propulsion system capability up to 100-kilowatt level and high-power plasma thrusters with direct utilization of electric power from lightweight, high-voltage solar cells • Aeroassist technologies for both aerocapture and direct-entry applications—lightweight thermal protection systems, active guidance and control, more precise predictive techniques, and optimized design tools • Propulsion systems for utilization of in-situ resource products • Long-term storage and in-space utilization of cryogenic propellants
Propulsion	<ul style="list-style-type: none"> • Very lightweight solar sails to counteract solar gravity, with achievement of sail characteristic acceleration better than 6 millimeter/second² • Use of ultrahigh-power lasers to accelerate light sails • Very high-power plasma thrusters • Matter-antimatter annihilation propulsion • Nuclear fusion propulsion



4.0 Strategic Technology Areas

In the previous section, the four Strategic Enterprises described their technology goals and needs in the context of their future missions. These mission-pull needs serve as the basis for the technology programs that are funded and managed by each of the Enterprises. However, as discussed in Section 2.2, there is a need to ensure that NASA as a whole is providing sufficient support for a select group of very advanced technologies that offer the promise of revolutionizing how NASA does business in the future. These Strategic Technology Areas were identified by the Office of the Chief Technologist in cooperation with the Enterprises, they have been endorsed by the Technology Leadership Council, and they have been reviewed by the NASA Advisory Council. They are:

Strategic Technology Areas
Advanced Miniaturization
Intelligent Systems
Compact Sensors and Instruments
Self-Sustaining Human Support
Deep Space Systems
Intelligent Synthesis Environment

In each case, these technologies include thought-provoking visions of future capabilities that could influence how NASA approaches a variety of its future activities. These technologies are not programs or line items in the NASA budget, but they serve as the *technology-push* in the annual process for developing the technology budget that was briefly described in Section 2. They also represent ideal opportunities for cooperative programs with university researchers, drawing on the innovation and expertise characteristic of the academic community. These technology areas will be revalidated on an annual basis, and it is assumed that they will change over a period of time.

A recent report, *Space Technology for the New Century*,¹ by the National Research Council (NRC) identified a group of high-risk, high-payoff key technologies, and it recommended a sustained level of research and technology funding for these areas. While there is not a one-for-one correspondence with the NASA Strategic Technology Areas, the two lists are closely related. Nearly all of the NRC technology areas are included in the Strategic Technology Areas and, in some instances, are needed to support goals associated with two or more Strategic Technology Areas.

4.1 Advanced Miniaturization

The miniaturization of electronics and related components over the past decade has already stimulated dramatic reductions in spacecraft size. As these efforts are continued and extended, new generations of NASA science and exploration missions will emerge.

The advances in electronics and computation will allow reconfigurable, autonomous, "thinking" spacecraft. Other miniaturization techniques, such as Micro Electro Mechanical Systems (MEMS), will enable the development of small sensor, communications, navigation, power, thermal, and propulsion subsystems with very low mass, volume, and power consumption that operate in the rigors of the space environment. These components, brought together into microsystems, will provide opportunities for entirely new space architectures, such as distributed networks of microprobes on planetary surfaces, nanorovers that drive, hop, fly, and burrow, and constellations of microspacecraft (see Figure 4.1-1) that make simultaneous measurements and function as a sparse array for innovative remote-sensing applications.

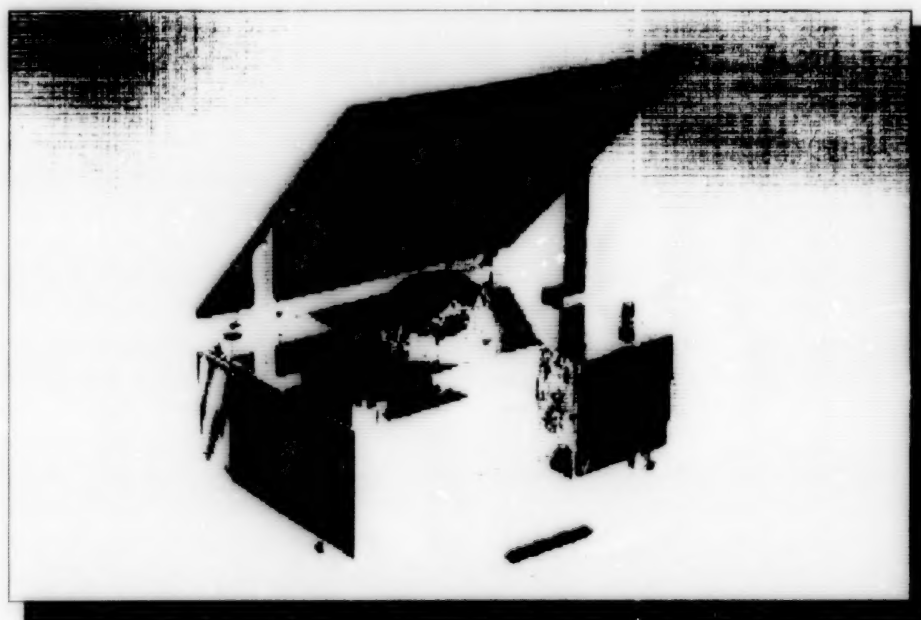


FIGURE 4.1-1. MOCKUP OF 5.5-KILOGRAM, 5-WATT "SECOND GENERATION MICROSPACECRAFT," WHICH COULD BE EXPLORING THE SOLAR SYSTEM WITHIN THE NEXT 10 YEARS

¹ *Space Technology for the New Century*, NRC, 1998.

On conventional spacecraft, both robotic and crewed by humans, miniaturization technologies will dramatically reduce mass, volume, and power consumption, thus lowering launch costs and providing new capabilities for science and human support. The same benefits apply to applications in aeronautics and space transportation systems.

Another significant benefit of miniaturization is the ability to increase mission reliability and survivability. This can be achieved by using more reliable and radiation-resistant microsystems and by using simple redundancy that is allowed when the microsystems are small and have very low-power consumption.

Advanced miniaturization not only serves many different customers but cuts across many technical areas and requires a multidisciplinary approach. These disciplines include physics, chemistry, biology, and electrical, mechanical, and aerospace engineering, which are applied to areas such as sensors, instruments, avionics, mechanisms, optics, robotics, propulsion power, communications, life sciences, life support, and space medicine.

Objective and Scope

The objective of the miniaturization thrust is to conduct research and development in technologies to enable new levels of miniaturization, integration, and power reduction in space and aeronautic systems. The thrust encompasses methods for reducing the size, mass, and power consumption of spacecraft, microlanders, and instruments. (Reduced power consumption translates into mass reduction because a smaller power system is needed, and it can also be enabling in power-starved missions.) These activities include design, analysis, fabrication, and test methods at the device and component levels. However, the thrust also includes new architectures and concepts for avionics, computational, communications, and space systems (such as microspacecraft and nanorovers) that are uniquely based on and enabled by miniaturization (e.g., MEMS, micro-optics, and nanotechnology). These new concepts will be enabled by miniaturizing components, together with new levels of architecture, systems integration, and advanced packaging. Advanced microelectronics and photonics technologies are included in this area.

Aeronautics and space transportation systems also require mass, volume, and power reduction. In addition, they need new levels of vehicle health monitoring that can be enabled by embedded microsensors and new levels of computation to make smart systems. Advanced miniaturization includes miniature aerospace systems (such as gyros and actuators) that have wide applications—basic to the overall reduction of spacecraft size—as well as demonstrations of MEMS technology for other areas. Note that aerospace systems are an application area in which advanced miniaturization activities require, or overlap with, discipline-level technologies not necessarily encompassed by other strategic technology thrusts. The miniaturization thrust will conduct research and development to ensure that the devices and microsystems will function in the harsh environment of space, which includes temperature extremes and radiation. The activities included in the advanced miniaturization thrust are listed in Table 4.1-1.

TABLE 4.1-1. ADVANCED MINIATURIZATION AREAS

<p><u>Micro- and Nanodevices</u></p> <p>Micro- and nanoelectronics</p> <p>Photonics</p> <p>Superconductivity</p> <p>Micromagnetics</p> <p>Quantum wells</p> <p>Detector devices</p> <p>Device physics and modeling</p> <p>Advanced materials</p> <p>Material and device fabrication and characterization</p>	<p><u>MEMS</u></p> <p>Micromachining techniques</p> <p>MEMS sensors (physical, chemical and biological)</p> <p>MEMS actuators</p> <p>Micro-optics and optoelectronics</p> <p>Radio frequency components</p> <p>LIGA (Lithographie Galvanoformung Abformung)</p> <p>Integration and packaging</p> <p>Space environmental compatibility (radiation, temperature, shock, failure mechanisms, and reliability)</p>
<p><u>Computation, Avionics, and Communications</u></p> <p>Revolutionary computing (biological/DNA, quantum, single electron, and superconducting)</p> <p>Neural networks</p> <p>Optical processing</p> <p>Scaleable, fault-tolerant flight computer</p> <p>Avionics sensors</p> <p>Low-power electronics</p> <p>Radiation-resistant materials and architectures</p> <p>Innovative radiation shielding</p> <p>Wireless sensors and systems</p> <p>Monolithic microwave integrated circuits</p>	<p><u>Microsystems</u></p> <p>Systems on a chip</p> <p>Mixed signal systems</p> <p>Smart sensors</p> <p>Architecture and systems analysis</p> <p>Hybrid bonding and packaging</p> <p>Reliability modeling</p> <p>Systems simulation and test</p> <p>Distributed networked microsystems</p> <p>Microspacecraft</p> <p>Microprobe:</p> <p>Nanorovers and nanorobots</p> <p>Constellations and microprobe networks</p> <p>Vehicle health monitoring system</p>

The miniaturization thrust will focus on the highest payoff technologies with a balance between technology-driven innovation and those serving the current established needs of NASA customers. Note that the NRC, in its report, has recommended increased investment in MEMS, radiation-resistant electronics, and wideband, high-data-rate communications.

Technical Approach

Micro- and Nanodevices. New micro- and nanoelectronics will enable quantum leaps in computing, communications, sensing, and signal processing. Advances will be accomplished by utilizing new materials, nanometer lithography, and unprecedented degrees of integration to make extremely high-speed, yet low-power devices. The potential of magnetic materials will be explored. An example of these new capabilities is displayed in Figure 4.1-2: a mixer, created by nanometer lithography, operating at terahertz frequencies, enabling new instruments for atmospheric study.



FIGURE 4.1-2. MONOLITHIC 2.5-TERAHERTZ MIXER INCORPORATING A 100-NANOMETER AIR-BRIDGED GALLIUM-ARSENIC SCHOTTKY DIODE (THE DIODE IS BEING DEVELOPED FOR THE EARTH OBSERVING SYSTEM MICROWAVE LIMB SOUNDER TO MEASURE OXYGEN-HYDROGEN EMISSIONS AS PART OF A STUDY OF OZONE CHEMISTRY IN EARTH'S ATMOSPHERE.)

Photonics in space enables miniature science instruments, very high-speed optical communications, real-time optical processing, metrology, and life support systems through the use of semiconductor lasers and integrated optoelectronic devices made from new material systems and novel structures. Figure 4.1-3 shows the tunable diode laser that enables precision spectroscopy on the Mars Polar Explorer mission. Photonics technology also will allow for the monitoring of emissions from high-speed aircraft and microsystems, such as a laser Doppler anemometer that will be used for the analysis of airflow around aircraft and space launch vehicles. Bandgap engineering achieved by molecular beam epitaxy and metal-organic vapor phase epitaxy (MOVPE) growth of III-V and silicon materials allows for a new family of heterostructure devices, such as quantum wells, which can be used as detectors in unique parts of the electromagnetic spectrum and for long wavelength semiconductor lasers for in situ sensing. Quantum cascade lasers are another example. Wide bandgap materials such as silicon carbon, gallium nitrogen, aluminum nitrogen, and diamond hold promise for high-temperature devices, high power electronics, chemical sensors, ultraviolet sensors, and blue-green and ultraviolet lasers for free-space optical communications. In the future, bandgap engineering will be applied to these material systems to achieve currently inaccessible spectral regions.



FIGURE 4.1-3. NARROW LINEWIDTH SINGLE-MODE COMPOUND SEMICONDUCTOR LASER MADE BY MOVPE AND NANOMETER LITHOGRAPHY TO MEASURE WATER AND CARBON DIOXIDE IN THE MARTIAN ATMOSPHERE (THIS LASER IS CURRENTLY MONITORING EARTH'S ATMOSPHERE FROM AIRCRAFT PLATFORMS.)

Superconductivity enables digital circuits operating up to hundreds of times faster than silicon while consuming much less power. Other applications are quantum-noise limited heterodyne receivers at frequencies above a terahertz, ultrasensitive bolometers in the infrared, and energy-resolving single-photon detectors from the visible to the x-ray spectral regions. Low-temperature superconductors will be integrated into million-gate chips and large detector arrays. High-temperature superconductors hold similar promise in the long term but with greatly reduced cooling requirements.

Comprehensive understanding of the material and device physics combined into models and simulations will enable rapid design and optimization of electronic and photonic devices and systems. These models combined with experimental testing will reveal failure mechanisms and lead to highly reliable systems. Modeling, combined with advanced materials and device characterization techniques, including scanning tunneling, atomic force, scanning electron and transmission electron microscopy, photoemission, and electrical, thermal, and optical property measurements, will lead to dramatic progress in material and device development.

MEMS. MEMS enable orders-of-magnitude reductions in the size, mass, and power consumption of aerospace systems. Examples of MEMS devices include micromachined silicon gyros (see Figure 4.1-4), accelerometers, seismometers, pressure sensors, valves, microthrusters, micropower sources, chemical and biological analysis systems, radio frequency, optical and mechanical filters, and radio frequency switches. Today's MEMS devices are standalone, usually in silicon,

with separate electronics. The vision for the future is of integrated MEMS microsystems micro-machined from silicon, III-V compound semiconductors, glass, ceramics, metals, and plastics with several functions and fully integrated electronics. New hybrid bonding techniques will allow for three-dimensional microstructures of semiconductors, metals, insulators, and other materials to enable integrated optomechanical micro-instruments and miniature chemical analysis laboratories. MEMS-based actuators and motors will have the ability to provide sufficient force and torque to replace conventional mechanisms, and MEMS will be a key technology for microspacecraft, microprobes, and nanorovers. Smart skins with active control surfaces will be available for aircraft and launch vehicles.

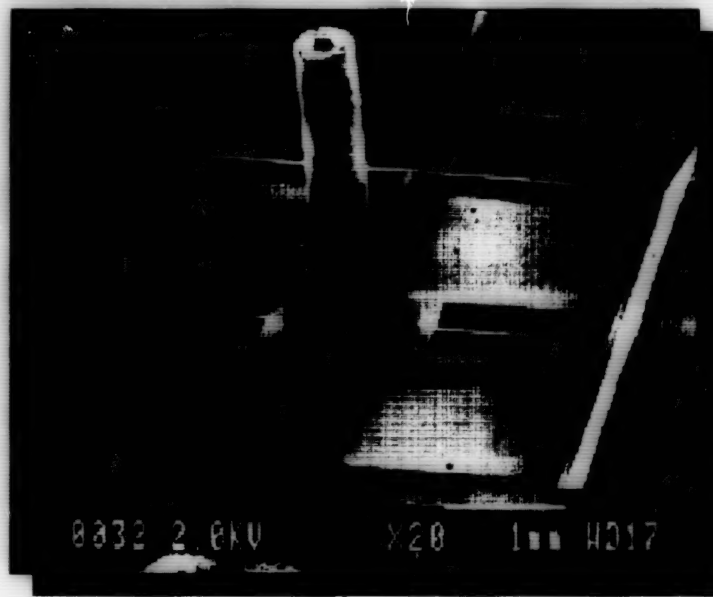


FIGURE 4.1-4. MEMS GYROSCOPE SHOWING THE RESONANT CLOVERLEAF STRUCTURE THAT IS THE ACTIVE ELEMENT OF THE GYRO (THE MEMS GYRO WILL FLY AS PART OF THE AVIONICS FLIGHT EXPERIMENT ON THE X-33.)

Micromachining techniques combined with electron beam lithography enable the surface of a material to be sculpted with a precision of 0.02 micrometer, which is a small fraction of the wavelength of light. Micro-optics in the form of analog surface relief diffractive optical elements enable compact high-performance optical instruments that cannot be realized using conventional optics techniques. Micro-optic gratings will enable new hyperspectral imaging spectrometers, holographic dispersers for imaging and optical processing, and lenslets for each pixel in a detector array. In Figure 4.1-5, one such high-efficiency grating is pictured; this grating enables a hyperspectral imager to be the size of a soda can. Techniques such as deep reactive ion etching and LIGA allow real three-dimensional MEMS structures to be made. LIGA uses x rays to make several millimeter-deep patterns in plexiglass into which metals can be electroplated. This opens up the MEMS area to metals that are used for gears, electromagnetic filters, and components for sensors such as mass spectrometers.

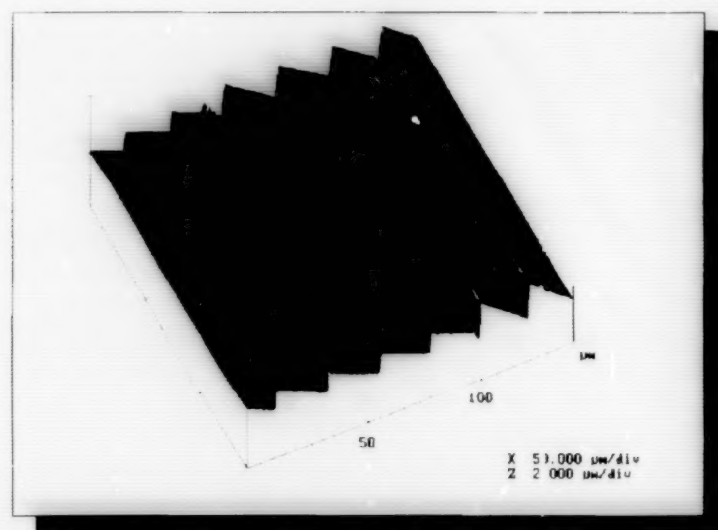


FIGURE 4.1-5. DUAL-BLAZE MICRO-OPTIC GRATING WRITTEN WITH ELECTRON BEAM LITHOGRAPHY ON A CONVEX SUBSTRATE (A SIMILAR SINGLE-BLAZE GRATING ON A CONVEX SURFACE WILL BE PART OF THE HYPERSPECTRAL IMAGING INSTRUMENT ON THE NEW MILLENNIUM EARTH OBSERVING-1 MISSION.)

A high-priority goal of the NASA Astrobiology program is understanding how life may have originated and persisted beyond Earth. Microfabrication techniques, including MEMS, will be used to miniaturize bioanalytical devices to enable their use on Mars and Europa. These include miniature capillary electrophoresis systems, DNA detectors, and chemical sensors and biosensors for in situ investigations of biosignatures. Many of these require wet chemistry and sample preparation, and microfluidics will play a key role. MEMS are an emerging field, and issues such as reliability, failure analysis, and packaging need to be thoroughly addressed.

Computation, Avionics, and Communications. Novel and revolutionary computing technologies will be pursued to leapfrog the "brute force" approach to prepare for the time (around the year 2010) when, according to the Semiconductor Industry Association Roadmap, we will reach the physical limits of feature-size reduction in silicon. Future computing technologies include optical processing, reconfigurable neural networks, single-electron, quantum, superconducting, and biological computing (see Figure 4.1-6). Biological systems have inspired artificial neural networks, and biological systems outperform supercomputers in tasks such as pattern recognition, sensor fusion, real-time control, adaptation to the environment, and learning. Miniaturized, highly parallel electronic or optoelectronic artificial neural network processors will perform real-time onboard information processing for science, autonomy, and vehicle health management. Optical processors coupled with neural networks will control autonomous precision landing and docking and enable change detection to recognize new science opportunities and detect space system anomalies. The combination of optical sensors and advanced computation will result in a fully integrated "eye-brain" module of a "thinking spacecraft."

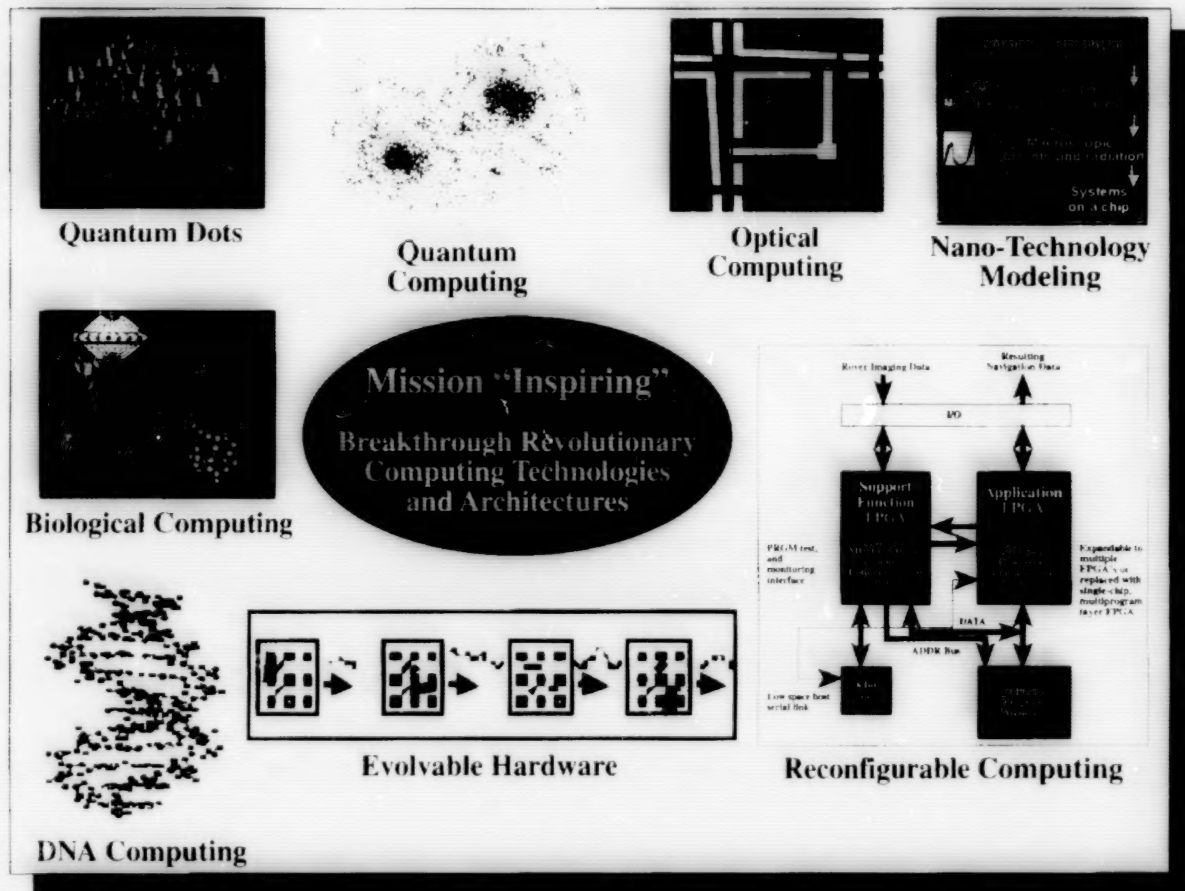


FIGURE 4.1-6. EXAMPLES OF REVOLUTIONARY COMPUTING TECHNOLOGIES BEING PURSUED UNDER THE ADVANCED MINIATURIZATION THRUST

Superconducting single-flux quantum logic will allow devices to operate at speeds many times that of semiconductors. Reconfigurable and evolvable hardware based on field programmable gate array technology will allow fully adaptive onboard computing. Quantum computers will be developed to solve intractable problems, and the potential of DNA computers will be evaluated.

High-frequency monolithic microwave integrated circuits (MMIC) will be pursued for their application to radar, millimeter, and submillimeter instruments and advanced communications systems. Performance and reliability modeling and simulation, coupled with system testing, will be used to rapidly converge on optimum designs. New low-power wireless communications technology will allow new levels of integrated sensor systems to monitor the health of rockets, spacecraft, and human space stations, as well as a network of science outposts on distant bodies. Miniature optical and radio frequency components will allow wideband, high-data-rate communications from anywhere in the solar system and beyond. These advances include digital radio frequency systems to increase stability and phased-array emitters for beam steering.

Future avionics architectures will be open and based on commercial standards with the goal of inserting commercial off-the-shelf technologies into space systems within 18 months of their

ground-based introduction. Scaleable, high-performance, but low-power, space computers using commercial laptop microprocessors will command the spacecraft and perform onboard autonomy calculations and science data analysis. The reliability needed by space missions will be provided by a combination of software-implemented fault-tolerance and radiation-resistant computer memories and electronics. New shielding techniques and protective materials, together with radiation-resistant electronics, will replace rad-hard parts in all but the most demanding applications. Miniaturized sensors such as accelerometers, gyros, and Global Positioning System (GPS) receivers will be integrated with flight computers into complete miniature avionics systems.

Microsystems. Systems on a chip will replace circuit boards with many discrete components, leading to much smaller and lower power systems with higher reliability. A current example is a digital camera on a chip that includes the imager, all-control electronics, and an analog-to-digital converter all on the same silicon chip (see Figure 4.1-7). Future systems on a chip will include both digital and analog circuits, including power and radio communications. These mixed-signal applications present a significant challenge in system architecture, analysis, and packaging. Systems on a chip technology will enable highly capable, autonomous microspacecraft by integrating all electronic functions into a single monolithic unit. Low-power and wireless communications devices will be combined with sensors and imagers to eliminate wires and enable wireless networks of sensors for science on distant planets and for health management on aircraft, launch vehicles, and human space stations. Smart sensors and imagers will result in new applications, such as an optical communications acquisition and tracking system on a chip.

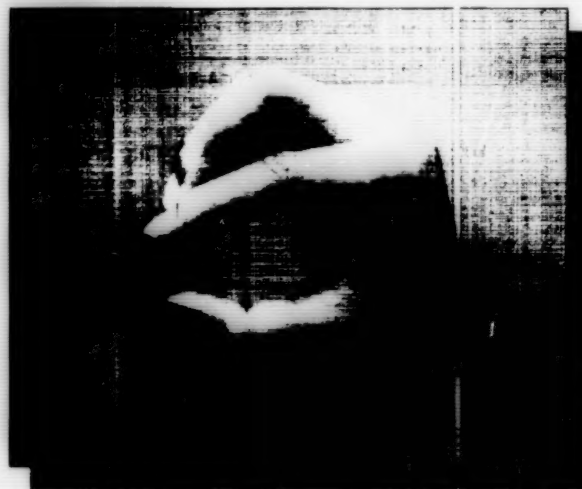


FIGURE 4.1-7. MINIATURE DIGITAL ACTIVE PIXEL SENSOR VISIBLE CAMERA WITH 256 BY 256 IMAGER, CONTROL ELECTRONICS, AND ANALOG-TO-DIGITAL CONVERTER INTEGRATED ON A SINGLE CHIP USING ONLY 20 MILLIWATTS OF POWER

Advances in silicon-based imaging technologies, such as the active pixel sensor, charged coupled device (CCD), and charge injection device offer the promise of ultralow power and extensive integration, high quantum efficiency, and high-speed random access readout. The imagers have applications in human missions, astronomy, planetary science, and Earth science.

This thrust will strongly pursue the architecture studies, systems analysis, and technologies that will enable future generations of microspacecraft, microprobes, and nanorovers for both science

mission applications and robotic assistants for humans on crewed missions. Miniature low-cost, highly autonomous spacecraft will allow for very frequent missions with low life-cycle costs. Fleets of microspacecraft powered by solar sails or miniature engines will be able to explore the solar system and beyond, as well as land on and burrow beneath the surface of any body.

Nanorovers and robots that drive, fly, hop, crawl, or burrow will provide unprecedented mobility on planetary bodies for science and exploration. Figure 4.1-8 shows a NASA designed 1-kilogram nanorover intended for surface exploration of asteroids. Groups of communicating and cooperating nanorobots or rovers will allow for large-area scientific investigations and provide "scouts" for human explorers. These microspacecraft, microprobes, and nanorobots are themselves enabled by the other technologies in the miniaturization thrust.



FIGURE 4.1-8. ONE-KILOGRAM NANOROVER FOR SURFACE EXPLORATION OF PLANETS AND ASTEROIDS (THE NANOROVER IS SCHEDULED TO FLY TO AN ASTEROID AS PART OF THE JAPANESE MUSES-C MISSION.)

Concomitant advances in a variety of nanofabrication technologies (among which are materials deposition, lithography, chemical etching, micromachining, rapid prototyping, and software design tools) will enable miniaturized chemical/biological laboratories—"labs on a chip." These are complete application-specific systems that will integrate fluid microhandling systems for extracting and reacting target molecules, microseparation technologies for enhanced sensitivity and resolution, and advanced detection technologies. Integrated microliter-scale bioassay systems are already under development for drug discovery, genetic analysis, and clinical diagnostics in the biomedical field. These miniature laboratory technologies can be tailored to address a wide range of NASA analytical needs, including the search for specific organic molecules that could provide information on the mechanism of prebiotic evolution or possible extinct and extant life. More generally, they can be tailored for detailed chemical and biological assessments, ranging from planetary surface and subsurface chemistry through planetary environmental monitoring and space-based clinical diagnostics.

Pacing Technical Issues

The following list (Table 4.1-2) provides a high-level view of important technical issues in each of the advanced miniaturization areas.

TABLE 4.1-2. ADVANCED MINIATURIZATION PACING TECHNICAL ISSUES

Micro- and Nanodevices	<ul style="list-style-type: none"> • Ultrafine electron-beam lithography • Precision etching • Wide bandgap semiconductors • High- and low-temperature electronics • Bandgap engineering in antimonide- and phosphide-based and wide bandgap materials • Quantum wires and dots • New superconducting materials, devices, and circuits • High-temperature superconducting devices • New materials (such as carbon nanotubes and biological) • Novel device structures • Physics of nanometer, low-noise, and high-power devices • Physics of radiation resistance • Heteromaterial bonding and hermetic sealing • Flip chip and hybrid packaging • Modeling and simulation
MEMS	<ul style="list-style-type: none"> • Micromachining of new materials (gallium arsenic, glass, metals, and ceramics) • New sensor concepts • Integration of multiple devices and electronics • Actuators capable of macroscopic action • Integrated chemical/biological analysis systems, such as sample extraction/preparation, microfluidics, and biosensors • Microthrusters, microvalves, and micropropulsion • Micropower Sources • Micro-optics and optomechanics • Space environmental effects • Reliability and failure analysis • Design tools • Hermetic packaging
Computation, Avionics, and Communications	<ul style="list-style-type: none"> • Realistic implementations of biological/DNA, quantum, and single-electron computation (DNA separation methods, 10-40 Qbit quantum computer, quantum dots, and robust error correction) • Neural processors and genetic algorithms • Learning algorithms • High-speed, large-format spatial light modulators/optical processing devices • Architectures for novel computational devices • Novel high-density data storage • Low-power scalable flight computer architectures • Commercial off-the-shelf parts in space • Software-implemented fault tolerance • Radiation effects on low-power high-density electronics • Innovative radiation shielding • Radiation-resistant materials (such as silicon on insulator) • Low-power wireless systems (networks and communications to the mother ship) • Mixed-mode ASIC design and virtual testing in "smart" systems • Digital radio frequency components
Microsystems	<ul style="list-style-type: none"> • Integration of sensors and electronics into "smart" systems • New generation silicon imagers • Mixed-signal silicon on insulator technology • Micron-scale hybrid bonding • Wafer-scale integration • Thermal and electromagnetic control • Architecture and systems analysis • Design tools, modeling, simulation, and test packaging • Vehicle health management architecture and systems • Microspacecraft, microprobe, and nanorobot architecture and systems • Inflatable sails and microengine • Microprobe and nanorover networks and communications • Nanomobility (driving, walking, hopping, flying, and burrowing) • Nano "workers" to scoop, dig, and assemble

All these pacing technology issues require significant investment to secure their benefits for NASA. As a subset of these issues, the advanced miniaturization thrust endorses the findings of the NRC report, which recommends additional modest focused investments in MEMS, radiation-resistant electronics, and wideband communications, which hold promise for large future benefits for NASA.

Partnerships and Related Activities

The advanced miniaturization thrust has particularly strong interactions with the intelligent systems and compact sensors and instruments strategic technology thrusts. In some instances, the contribution from advanced miniaturization will be simply to make things small. In others, a new fundamental technique, such as quantum tunneling, is basic to advanced miniaturization. Concepts for quantum computing are principally the domain of intelligent systems, while the means to fabricate them are in the domain of advanced miniaturization. Bandgap engineering techniques leading to quantum well detectors and lasers and superconductivity used to develop efficient high-frequency mixers are part of advanced miniaturization, but their use in science instruments is under compact sensors and instruments.

Advanced miniaturization will benefit from the intelligent synthesis environment and intelligent systems technologies. The intelligent synthesis environment will provide an advanced modeling and simulation environment that will be used for device and microsystem modeling under miniaturization. Intelligent systems will provide advanced conceptual approaches that will be integrated into miniaturized systems to create small, "smart" systems.

Miniaturization of NASA space systems has significant overlap with the needs and programs of other agencies and organizations. These include the U.S. Air Force, the National Reconnaissance Office, the Ballistic Missile Defense Organization (BMDO), and the Defense Advanced Research Projects Agency (DARPA). NASA has ongoing relationships with these organizations, and new partnerships will be established to ensure a coordinated and synergistic national investment in miniaturization. In addition, NASA will promote relationships with organizations such as the National Science Foundation (NSF), the National Academy of Sciences, the National Oceanic and Atmospheric Administration, and the external science community to maintain our balance of technology innovation and user pull. Furthermore, NASA as a mission agency will leverage the national investment in the technical advances made by universities. The NSF makes much of the national investment in universities, and NASA will work with the NSF to cosponsor mission-oriented research at universities.

Industry, particularly in electronics and communications, is driving many of the areas critical for the miniaturization of NASA systems. NASA will aggressively utilize these advances and form partnerships with industry to meet Agency needs. In addition, technological advances made by NASA will be transferred to industry partners for commercialization.

4.2 Intelligent Systems

NASA's bold missions in space exploration (Figure 4.2-1) and aeronautics will require advances in many areas of science and technology, and among the most critical of these enabling

technologies are information technology and, more specifically, intelligent systems research. The information technology revolution at NASA is twofold—first, and most obviously, computer technology is enabling new missions at lower cost; second, NASA is starting to understand itself as an information technology agency.



FIGURE 4.2-1. UNDERWATER
EUROPA MISSION
CONCEPT

tions and missions, some of which we can only dimly glimpse today while others seem obvious. In Table 4.2-1, we have identified five mission-critical application areas with the objective of transforming them through the application of intelligent systems. We will take these critical application areas, each in turn, discussing how the anticipated results of intelligent systems research will be the cornerstones that enable new missions at lower cost while helping NASA to meet its aeronautics “stretch” goals.

The thrilling and fiery launches and, in fact, the spacecraft themselves are critical, but increasingly ancillary, to the real purpose, which is to get our computers and sensors on station so that they might tell about the distant worlds they visit. The recent Mars Pathfinder mission is an example of a publicly engaging, interactive mission of virtual presence on the Martian surface.

Objectives

The pervasive nature of, and our increased dependency on, information technology, coupled with the leveraging nature of intelligent systems, will enable a wide range of applica-

TABLE 4.2-1. MISSION-CRITICAL APPLICATION AREAS

<i>Mission-Critical Application Areas</i>	<i>Research Cornerstones</i>
Autonomous Spacecraft and Rovers	Automated Reasoning
Science Data Understanding	Intelligent Systems for Data Understanding
Aviation Operations	Human-Centered Computing
Intelligent Synthesis Environment	
Human Exploration of Space	

Autonomous Spacecraft and Rovers. NASA’s mission of deep space exploration, coupled with Administrator Goldin’s challenge to do it “faster, better, and cheaper,” has provided the requirement for one of the most exciting challenges facing the computer science research community—that of designing, building, and operating progressively more capable autonomous spacecraft, rovers, planes, and perhaps even submarines. When one considers the distances involved in deep space missions, and the attendant communication delays, the value of autonomy becomes clear.

NASA is planning to fill space with robotic explorers, carrying our intelligence and our curiosity, to explore the universe beyond in ways never before possible. This robotic exploration of space is already well under way. Our new surrogate explorers need to be smart, adaptable, curious, wary, and self-reliant in harsh and unpredictable environments. A roadmap for spacecraft autonomy is given in Figure 4.2-2.



FIGURE 4.2-2. ROADMAP FOR SPACECRAFT AUTONOMY

In addition to spacecraft, there are other types of robotic explorers with the requirement for autonomy, such as planetary rovers. Uncertainty about hazardous terrain and the great distances from Earth will require that the rovers be able to navigate and maneuver autonomously over a wide variety of surfaces and independently perform science tasks. Rovers will need to become progressively smarter and more independent as their roles expand to include surveying and evaluating potential science sites, recognizing science opportunities, gathering samples, and perhaps conducting some onboard analysis.

In addition to autonomy for commanding and self-diagnosis, there is an increasing need for an autonomous or semi-autonomous onboard science capability (see Figure 4.2-3). Deep space probes and rovers send data back to Earth at a very slow rate, limiting the ability of the space science community to fully exploit the presence of our machines on distant planets. Thus, a requirement exists for research aimed at developing a new framework for performing data evaluation and observation planning autonomously aboard spacecraft—that is, the spacecraft should have some idea of what humans would be interested in, and they must not send back every bit of information, but only those that count.

Our limited communications bandwidth would be used in an extremely efficient fashion, and “alerts” from various and far-flung platforms would be anticipated by the science community with great interest. New onboard science capabilities will enable mission activities to be directed by scientists without the assistance of a ground sequencing team, increasing the return of quality science products while accommodating the twin realities of limited communications links and reduced operating budgets.

PROCESSING

One of the clearest and most compelling examples of the need for research on automated reasoning for autonomous systems is the requirement for in situ propellant production for both the Mars Sample Return mission and any economically feasible plan for the human exploration of Mars. Most envisioned scenarios for a human mission to Mars depend critically on a robotic lander that will set up a largely autonomous chemical plant to synthesize from the Martian atmosphere the necessary rocket propellant to bring the astronauts home.

Closer to home, the use of autonomous systems to monitor payload health continuously prior to launch will greatly expedite their integration and checkout in the very short turnaround times expected of next-generation Reusable Launch Vehicles. Capturing the knowledge of payload developers and test engineers in these systems will also reduce the personnel costs inherent in the current process. Autonomous payload health monitoring systems will also provide us with a test-bed for autonomous spacecraft systems, with the ability to observe and improve their performance directly.

Relevant research areas for autonomous spacecraft and rovers include, among others, fast deduction, planning and scheduling systems, search engines, model-based monitoring, diagnosis and recovery, pattern recognition, data summarization and data mining, modeling and simulation, software development tools, end-to-end architectures, automated code generation, and advanced integration and test tools. Research on automated reasoning for autonomous systems will enable a new generation of spacecraft to perform more exploration at much lower cost than traditional approaches.

Science Data Understanding. NASA is responsible for launching and gathering data from progressively more sophisticated orbital and deep space instruments. For example, the Earth

Observing System (EOS) is being deployed to monitor global climate change. When fully operational, these sensor-rich satellites will generate about 1 terabyte of data per day. In addition to the obvious need for progress in high-capacity data storage and dissemination schemes, the development of tools aimed at facilitating human understanding of these immense data sets is equally important. It is in this area that intelligent systems research can have a great impact on the ability of scientists on Earth to more fully understand and exploit the unprecedented amounts of data that NASA is now collecting. In particular, research will be needed in the areas of statistical methods for image enhancement and analysis, machine learning, and automated knowledge discovery and data mining methods.



FIGURE 4.2-4. AIR TRAFFIC CONGESTION

Aviation Operations. Here on Earth, many of these same intelligent systems technologies will provide the catalyst for revolutionary improvements in the Nation's air traffic management systems. The projected growth in air traffic over the coming decade will strain our already congested air traffic (Figure 4.2-4) and ground management systems, producing an unacceptable number of accidents if nothing is done. President Clinton has announced a major initiative to increase the safety and capacity of the aviation transportation system. NASA, in collaboration with the Federal Aviation Administration, is devel-

oping advanced information technology systems that will play a major role in realizing the twin goals of safer aircraft operation and higher throughput of the airport and ground control infrastructure.

Applications of intelligent systems research could include automated planning and scheduling for airport ground operations, dynamically reconfigurable aircraft, automated landing procedures, autonomous fault isolation and repair, and a new generation of performance support systems to assist pilots and air traffic controllers alike. However, as aviation systems become increasingly capable of independent initiative, the problem of how the crew and the autonomous systems will interact in these mixed-initiative systems becomes of central importance. This realization leads to the clear requirement for increased research in what has become known as human-centered computing.

Intelligent Synthesis Environment. Clearly, the future missions of NASA, such as Mars exploration, as well as many of the Aeronautics "stretch goals," involve uniquely difficult design and engineering challenges. To address these challenges, NASA will invest in the intelligent synthesis environment strategic technology to exploit advances in intelligent systems research in general and human-centered computing in particular. The intelligent synthesis environment strategic technology program is described in Section 4.6.

Human Exploration of Space. As humans contemplate journeys to Mars and beyond, NASA will clearly need to exploit a wide range of intelligent systems that operate autonomously or semi-autonomously in support of mission requirements. Some obvious applications areas include diagnosis, automated planning and scheduling, condition-based maintenance, and performance support systems for astronauts and ground operations personnel.

A critical requirement for NASA is to reduce the cost of operating in space. Fortunately, it is anticipated that advanced information technology research will lead to dramatic reductions in launch and operational costs of space flight systems. In particular, research on human-centered computing, focused on developing powerful performance support tools to extend and leverage the capacities of the ground controllers, can be expected to radically lower operations costs by reducing the staffing requirement. The problem domain of planning the integration and checkout of launch vehicles can, for example, involve the management of 4,500 tasks and 60,000 constraints. Errors or inefficiencies can result that delay the launch, adding millions of dollars to operations costs. Increasing efficiency on the ground can, conversely, reduce the cost of access to space for mission after mission.



**FIGURE 4.2-5. ASTRONAUTS WORKING
IN SPACE**

capabilities: environmental monitoring, crew worksite support, communications, and remote operations support. Such innovative applications are possible, in the near-term future, composed entirely of commercial off-the-shelf/Government off-the-shelf hardware controlled by sophisticated intelligent systems software.

Likewise, intelligent systems research will greatly extend the capacities of astronauts (see Figure 4.2-5) while reducing the risks inherent in space exploration. For just one of many possible examples, consider the Personal Satellite Assistant (PSA) now in research phase—a softball-sized crew performance support device designed to move and operate autonomously in the microgravity environment of space-based vehicles, such as the Space Shuttle, International Space Station (ISS), and any future exploration spacecraft. The PSA will provide the following crew support

Technical Approach

During the past 2 years, there have been several, sometimes uncoordinated, efforts focused on ascertaining NASA's future intelligent systems requirements conducted by various groups, ranging from a multi-Center team of NASA information technology researchers producing a report called "Thinking Spacecraft," to the Autonomy and Information Management planning process, to the various advisory committees (including top-drawer academic and industrial advisors) of the NASA Challenge of Excellence for Information Technology, which has recently produced a multi-Center document titled "Information Technology at NASA: Accepting the Challenge of

Excellence." As a result of these efforts, we have converged on three research cornerstones on which NASA can build its intelligent systems future:

- Automated reasoning
- Intelligent systems for data understanding
- Human-centered computing

Automated Reasoning. To accomplish NASA's ambitious exploration goals, researchers must develop autonomous control kernels that can be commanded by simple, high-level, goal-directed behaviors, such as "make an attitude determination followed by a course correction" or "find the next most interesting rock close by and move to it." These robotic explorers will be programmable through compositional, commonsense models of hardware and operations behavior. This goal-directed, model-based programming paradigm will allow control systems of spacecraft to be plugged together like Lego blocks from libraries of existing models, and it will permit novel behaviors to be programmed in a simple intuitive manner. Using these models on board, the automation will close the loop on sensor information at the goal level, using advanced deductive planning and execution, scheduling, diagnosis, and recovery capabilities to ensure that goals are being met. This programming paradigm has already demonstrated its usefulness in the Remote Agent Autonomy Architecture (RAAA) slated for demonstration (as an experiment) on the Deep Space 1 mission. NASA technologists should continue to develop and exploit the RAAA aggressively for application to future missions.

Achieving capable intelligent robotic explorers will require bold new research efforts designed to borrow from nature's secrets and emulate biological solutions to sensory perception, adaptation, and motor control. Intelligent autonomous systems will need to learn from their interactions with their environment and adapt appropriately in real time. By coupling biologically inspired neurotechnology with model-based reasoning, hybrid systems are envisioned that will use symbolic deductive methods to help coordinate and direct a collection of these adaptive methods.

As mentioned above in the "Autonomous Spacecraft and Rovers" section, our autonomous spacecraft will need to take their own initiative and adapt to their environment based on their curiosity and wariness. Curiosity can be understood as the ability to take action to gain information and draws on such research disciplines as planning of information acts, decision and information theory, decision theoretic planning, model-based reasoning, machine learning, and statistics. Wariness can be understood as involving the ability to assess risk, to plan contingencies and prepare backup resources, or to redirect plans to reduce risk. Research disciplines needed to develop this capability adds to the list of contingent planning, reasoning under uncertainty, Markov decision processes, and Bayesian inference. Wariness also requires an ability to anticipate and adapt to subtle cues that indicate deviations from the nominal path.

While exploring the universe, these automatons will often not act alone. For example, spacecraft carrying optical units will fly together in formation to create a single deep space interferometer of unprecedented size, or a swarm of microrovers might spread out to explore a patch of Mars. Achieving this level of teamwork requires distributed coordination and collaboration capabilities. Developing this capability will necessitate advances in distributed artificial intelligence, including distributed diagnosis, resource management and execution, coordination of heterogeneous

reasoning methods, and novel coordination mechanisms taken from diverse disciplines, such as organization theory, operations research, and economics.

Intelligent Systems for Data Understanding. Technology for onboard science data processing, along with advances in telecommunications technology, can address the challenge of limited communications bandwidth, which may worsen if NASA's vision of flying more space platforms at once is realized. Through onboard decisionmaking, scientist-trained recognizers, and the judicious use of knowledge discovery methods, a portion of the scientist's awareness can be projected to the space platform, providing the basis for scientist-directed downlink prioritization and the processing of raw instrument data into science information products. This software-based partnership between scientist and space platform can evolve during the mission as the scientist becomes increasingly comfortable with the direct relationship with the space platform, as intermediate scientific results emerge, and as scientist-directed software updates are uploaded.

In addition to the aforementioned need for research leading to increased onboard science data processing, NASA technologists must find ways to help scientists on Earth understand the growing morass of data currently being warehoused. This necessary research will include biologically motivated approaches such as neural networks and genetic algorithms, KDD (knowledge discovery and data mining) research, Bayesian methods as applied to the analysis and automatic classification of data, and statistical approaches that combine information from multiple images of planetary surfaces to form a surface model at higher resolution than any particular image. Because these emerging data-understanding methods have application to data originating from both deep space and Earth-orbiting spacecraft, NASA information technology research is better enabling scientists to understand our world as well as distant worlds.

Human-Centered Computing Research. The emerging concept of human-centered computing represents a significant shift in thinking about information technology in general and about intelligent machines in particular. It embodies a systems view, in which the interplay between human thought and action and technological systems are understood as inextricably linked and equally important aspects of analysis, design, and evaluation. Within this framework, NASA researchers are busy inventing and deploying sophisticated computational aids designed to amplify human cognitive and perceptual capabilities. Essentially these are cognitive prostheses—computational systems that leverage and extend human intellectual capacities, just as the steam shovel was a sort of muscular prosthesis.

The prostheses metaphor implies the importance of designing systems that fit the human and machine components together in ways that synergistically exploit their respective capacities. The design and fit of these computational prostheses often require an interdisciplinary effort, including computer scientists, cognitive scientists, and social scientists of various stripes. This shift in perspective places human-machine interaction issues at the center of the subject and requires a systems view in which the "system" in question is not "the computer," but instead includes cognitive and social systems, computational tools, and the physical facilities and environment.

Extending the prostheses metaphor to knowledge, systems that represent scarce and exceptionally valuable knowledge can be used to distribute that knowledge throughout a workforce, supplement the knowledge of personnel in critical positions, or give our industry partners an edge in the

international marketplace. These applications range from "best practice" enhancements of major activities, such as managing the acquisition and utilization of launch services, to making specialized knowledge of hazardous material handling available anywhere, anytime.



Human-centered computing may thus be defined as the discipline of integrating computer hardware and software with human performance and capabilities (see Figure 4.2-6) into a system that augments the capabilities and performance of both elements toward a specified goal or objective. This integration is grounded in an understanding of how people and computational systems differ, suggesting what role tools can most effectively serve and how they should be designed.

FIGURE 4.2-6. ADVANCED INTERFACE
FOR INTEGRATED TOOLS

Pacing Technical Issues for Intelligent Systems Research at NASA

Considering these three research cornerstones, many technical issues exist before intelligent systems become a reality. Table 4.2-2 is a list of the pacing technical issues for intelligent systems research.

Other Activities That May Contribute

In today's era of constrained budgets, it is particularly important that, wherever possible, NASA be a smart, demanding customer for information technology. We should look to partner with and leverage off industry, academia, and other Federal agencies to the greatest extent possible. If we reinvent many wheels, or try to build them all ourselves, NASA will not be able to afford to perform much space exploration. That said, there are problems that Silicon Valley is not going to solve for us, and in those areas, we must endeavor to perform and support some of the best research in the world.

The Department of Defense is sponsoring significant relevant research in several areas, specifically software agents, haptic interfaces, next-generation Internet-based tools for performance support and just-in-time training, biologically motivated computing, and other areas. NASA is well positioned to leverage this work effectively. In addition, the NSF sponsors a wide range of basic intelligent systems research of potential relevance to NASA. For example, NASA's human-centered computing effort is well coordinated with the NSF and with the Defense Department's extensive efforts in this area through a cross-agency working group (10 agencies are represented) that meets monthly.

TABLE 4.2-2. PACING TECHNICAL ISSUES FOR INTELLIGENT SYSTEMS RESEARCH

Automated Reasoning	<ul style="list-style-type: none"> • Model-based reasoning and programming research • Planning and scheduling research • Constraint-based reasoning research • Fast deductive inference and supporting architectures • Advanced software engineering for autonomy research: <ul style="list-style-type: none"> – Model-based test generation – Analytic verification methods • Onboard science data analysis and data mining • Smart reconfigurable computers • Declarative simulation research • Machine vision and navigation • Machine learning research • Biologically inspired sensor fusion and sensory-guided motor control • Adaptive learning and distributed cooperative learning agents • Intelligent execution and control • Collaborative autonomous systems research • Reasoning under uncertainty • Markov decision processes • Bayesian inference
Intelligent Systems for Data Understanding	<ul style="list-style-type: none"> • Statistical approaches to analysis and classification • KDD (knowledge discovery and data mining) research • Pattern recognition research • Neural network research • Machine learning research • Three-dimensional surface modeling • Advances in intelligent, content-based searching • Evolutionary design tools • Artificial collective intelligence research
Human-Centered Computing	<ul style="list-style-type: none"> • Performance support systems research • Just-in-time training systems research • Personal digital assistants and wearable computing research • Human-centered design tools (that is, cognitive prostheses for design) • Knowledge acquisition and design knowledge capture research • Natural language systems • Human cognitive, performance, and perceptual modeling and research: <ul style="list-style-type: none"> – Human information-flow modeling – Cognitive task analysis research – Research on decisionmaking under stress – Research on the nature of expertise – Research on multiperson performance modeling • Collaboration tools for scientists and engineers • Innovative human-machine interfaces and displays (such as haptics) • Next-generation Internet tools (such as browsers) • Intelligent software agents • Virtual reality and other simulated environments • Case-based reasoning

4.3 Compact Sensors and Instruments

Compact sensors and instruments comprise a strategic technology that is of fundamental importance to the success of NASA's Space Science and Earth Science Enterprises and plays a crucial supporting role in both the Human Exploration and Development of Space and the Aero-Space Technology Enterprises. Mission success of the two science enterprises directly depends on the availability of remote-sensing and in situ sensing systems that enable new and/or improved measurements of scientific parameters from a variety of surface, airborne, and spaceborne platforms and that reduce the cost to carry out those missions. Without continued improvements and innovations in this area, progress in space and Earth science will be severely restricted. Improvements in the human exploration of space, space development, aeronautics, and space transportation also directly depend on systems that accurately measure a wide variety of hardware performance and environmental characterization parameters.

As NASA ventures into an era of increasingly constrained resources, the next generation of sensors and instruments must be innovative in their scientific and technological capabilities while conserving limited resources, such as mass, power, volume, and end-to-end cost. Systems that use minimal resources are generically designated "compact"; however, the term does not exclude systems that inherently require large resource allocations. In these cases, compact refers to the decrease, typically by an order of magnitude or more, of the required resources in comparison to state-of-the-art systems.

Objectives

Generating a new set of compact sensors and instruments based on the development and infusion of cutting-edge technology will enable significant increases in mission performance and capabilities while reducing the costs of scientific measurements. Developing compact sensors and instruments has always been a NASA goal, but this objective has often been compromised to meet stringent performance requirements using available technology. In the future, compactness is to be considered a necessity to achieve affordable missions and to drive the development of instrument architectures and technologies that enable classes of missions heretofore unattainable.

Each of the NASA Enterprises has articulated its science research plans and associated capability needs, as captured in Enterprise Strategic Plans and other technology planning documents and as summarized in Section 3 of this document. This section highlights the technical objectives in the area of compact sensors and instruments expected to offer the greatest benefit to NASA in achieving these ambitious plans at an affordable cost. Although specific applications for future sensor systems vary across the NASA Enterprises, the desired advances can be summarized in the following categories:

- Receivers/detector systems
- Compact instrument architectures
- Active sensor systems
- Integrated payloads

Technical Approach

To meet these objectives, the new generation of compact sensors and instruments will depend on innovative systems engineering and the development of key technologies. Four broad technology classes have been identified above as likely candidates for significant advances and, therefore, likely to have a major impact on the development of the next generation of compact sensors. Each is discussed below in terms of recent developments and possible areas of enhancement. These are to be considered as examples of research and development tasks; they do not constitute a complete list.

Receivers/Detector Systems. Driven primarily by military surveillance needs, the development of high-sensitivity, large-format CCD arrays initiated a great leap forward in high-resolution imaging benefiting both space and Earth science applications. Recent advances in "smart sensor" arrays incorporating active electronics at the pixel level offer flexibility and simplicity in readout architectures. Further advances are desired to achieve higher levels of on-focal-plane integration to incorporate more sophisticated signal processing as well as micro-optics for beam focusing and filtering. Many measurements also call for larger full-well capacity per pixel. Advanced array architectures produce instrument capability enhancements in terms of image pixel count, dynamic range, measurement speed, instrument size, flexibility and simplicity of operation, and insensitivity to background radiation, and in some cases, they enable types of measurements that were simply not practical with previous technologies.

The extension of detector array technologies into other wavelength ranges translates directly into a concomitant extension of imaging and spectrometry instruments. For example, the Department of Defense investment in HgCdTe and InSb technologies has led to the availability of moderate-to-large-format arrays covering the near and thermal (mid) infrared (IR) regions. Further development for lower readout noise, dark noise, and larger formats are required. IR arrays that do not require active cooling are also desirable for reducing the power and size of future instruments. The far IR region, replete with scientifically valuable species-specific molecular and atomic spectra, has not been comparably developed. Quantum-well infrared photodetector technology has the potential for extending low-cost, large-format arrays through the thermal IR into the far IR. Further development of arrays in the highly sensitive silicon impurity-band conduction technology is also desired. On a longer time scale, bandgap-engineered materials discussed under the "Advanced Miniaturization" section above offer high sensitivity across the far IR. To achieve the highest sensitivities in the IR requires that both the optics and focal planes be cooled to cryogenic temperatures. Long-life, low-vibration, high-efficiency coolers are therefore required.

Array technology for ultraviolet (UV) light also needs improvement. Long-term solutions include arrays based on visible-blind wide-bandgap semiconductor, such as the nitrides and diamond. In addition, improved microchannel plates for fast timing, zero read noise, and visible-blind applications may be fabricated using lithographic manufacturing techniques.

High-energy astrophysics missions would greatly benefit from improved arrays. Development in materials and fabrication processes could enable a new generation of devices with deeper depletion depths to extend the response to higher energies and with an increased resistance to radiation damage. In other devices, changes in gate structure would enable the bandpass to be extended toward lower energies. For several of the high-resolution x-ray spectrometer technolo-

gies, such as cryogenic calorimeters, there is a need to develop construction and readout schemes that will allow for the production of large-format arrays. At higher energies, arrays based on materials such as CdZnTe should allow for the development of imaging gamma-ray spectrometers that would be significantly more compact than those using older technologies that require low operating temperatures.

The application of some of the detector technologies developed for experiments at the large accelerators could enable a new class of measurements of cosmic rays. Advanced, two-sided Si strip detectors, scintillating optical fibers, and solid-state replacements for photomultipliers, along with accompanying ASIC's to read and preprocess the outputs, could greatly advance the field.

Coherent IR, submillimeter, and millimeter radiometers and spectrometers provide high spectral resolution capable of detecting and identifying chemical species and directly measuring gas velocities (winds) in terrestrial and planetary atmospheres and in astrophysical sources. Miniature low-mass, low-power heterodyne receivers in these wavelengths (10 micron to about 1 millimeter) must be developed. Important areas of development include local oscillators, mixers, compact optics, and array capabilities. Array technology is particularly engaging because it would provide spatial as well as spectral information.

The extension of millimeter-wave MMIC technology to 700 gigahertz is desired, with an emphasis on power reduction and wide spectral bandwidth (Figure 4.3-1). Low-power spectrometers with upward of 100 channels and millimeter-wave array optics incorporating about 50 equally spaced fields of view are desired for future atmospheric limb sounding missions.

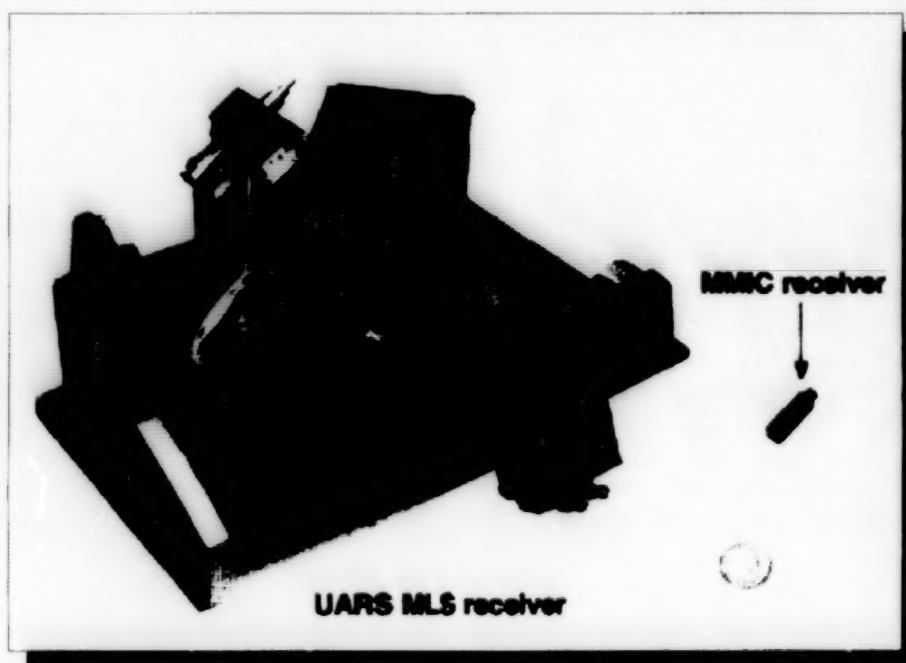


FIGURE 4.3-1. DOWNSIZED MICROWAVE LIMB SOUNDER RECEIVER USING MMIC TECHNOLOGY

A broader range of environmentally important chemical species can be detected and studied by extending the frequency range into the terahertz regime. The greatest challenge at these frequencies for heterodyne radiometers is generating the required 1–10 milliwatts of local oscillator power. Reducing the power requirement with new detector mixer schemes is also possible. High-speed metal-semiconductor-metal photodetectors are being pursued to address this need. Superconducting bolometer mixers with photo-mixer local oscillator sources implemented in both low critical temperature and high critical temperature represent another promising approach. Compact, efficient coolers are also required, cooling to 60 degrees Kelvin for high-critical-temperature systems and to 2 degrees Kelvin for low-critical-temperature systems. Imaging array technology in millimeter and submillimeter wavelength heterodyne systems is also emerging.

Infrared systems enable the study of important molecular species at a higher spatial resolution and probe additional pressure regions. The goals of infrared heterodyne spectrometer development consist of semiconductor laser and miniature gas waveguide laser local oscillators stable to 100-kilohertz, broadband (> 3 gigahertz) mixers, extending capabilities into wavelength regions longward of 12 microns and developing array spectrometers. Approaches include developing semiconductor and quantum-well technologies for lasers, as well as interdigitated electrode resonant optical cavity and quantum-well approaches for mixers and mixer arrays. Unique optical designs, including holographic optics, need to be developed for the generation and combination of arrays of signal and local oscillator beams.

The next-generation broadband measurements of Earth's radiation budget will require detectors that are spectrally flat from 0.6 to 100 microns, with an order-of-magnitude increase in sensitivity. High-temperature superconductor bolometers currently offer a fourfold improvement in sensitivity and are the best candidates for achieving the 10 fold improvement in sensitivity at the required wavelengths. Developments in thermopile and thermistor bolometer technology may enable some advances.

Compact Instrument Architectures. The size and power requirements of remote-sensing instruments can be reduced through innovative architectural approaches. Comprehensive measurements of atmospheric chemistry (gases, temperature, and moisture) can be achieved with wedged-filter imaging spectrometers or Fourier Transform Spectrometers operating from the visible through the far IR region. Novel Fourier Transform Spectrometer designs need to be developed to enable an order-of-magnitude reduction in spacecraft resources while preserving the quality of the science return. One advance is the development of smooth diamond membrane beamsplitters that can cover 1 to 1,000 microns in wavelength, thus permitting a much smaller system. Other spectrometer approaches should be examined, including acousto-optic tunable filter spectrometers and hyperspectral systems. Acousto-optic tunable filter spectrometers need to be extended through the thermal IR region. Hyperspectral imaging (nearly simultaneous spectral imaging at multiple wavelengths) can be improved using innovative grating and prism optical systems.

Many space and Earth science applications require large collection apertures to detect very weak signals, to achieve high spatial resolution, and/or perform other collection or shielding functions. Examples include deep space imaging, microwave imaging of soil moisture, outer planet solar energy collection and communications, and sun shields for mission flying close to the Sun. A number of innovative approaches are being pursued to achieve large-area collection optics in the operational configuration, while maintaining low mass and short linear dimensions during launch

(Figure 4.3-2). These include segmented optical surfaces, inflatables, deployables, and sparse (unfilled) aperture architectures. For high-resolution imaging, surface conformation must be held to within a fraction of the wavelength of the light being detected, resulting in very demanding precision surfaces and element control for imaging at optical and near-optical wavelengths.

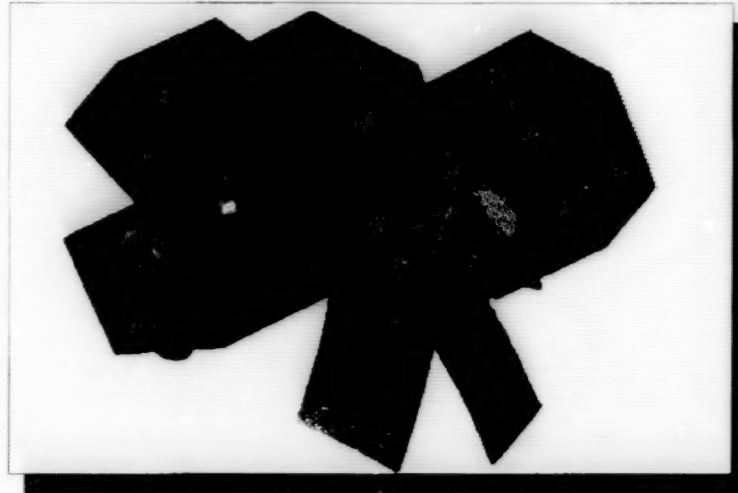


FIGURE 4.3-2. LIGHTWEIGHT, DEPLOYABLE TELESCOPE REDUCES MASS AND LAUNCH VOLUME

The emerging technologies of holographic and lithographically defined optics enable the automated manufacture of significantly more complex optical elements and the concomitant simplification of the physical optical system. Lithographic optics can also improve the performance of optical systems by reducing system aberrations. On-chip electronically tunable filters can eliminate both the bulk and wear vulnerability of moving parts in scanning optical systems.

There is also a need for low-mass, low-power, miniature, high-reliability scanning and actuator systems for remote-sensing instrumentation. These systems may use an all-solid-state, electro-mechanical motor based on advanced polyimide and ferroelectric materials. This technology will enable new remote-sensing instrument configurations that are consistent with a sensorcraft paradigm. The use of appropriate composite materials in instrument mechanical structures, components, and optics can permit lighter and stronger systems with better thermal and mechanical properties.

Active Sensor Systems. Spaceborne lidar offers a powerful new tool for profiling physical and chemical properties of atmospheres as well as for measuring topographic and gravitational properties. Reliable, efficient laser transmitter sources are required for Earth and planetary remote-sensing science missions (Figure 4.3-3).

Two classes of laser transmitters are targeted for near-term (0 to 5 years) development. The first class is either tunable or fixed frequency, with output energies from 0.1 to 1.0 joule at 10 to 100 hertz, with 3- to 50-nanosecond pulses, with 0.2- to 100-picometer stability, and wall plug efficiencies greater than 5 percent. These laser systems must produce outputs in the wavelength region from the UV to the mid-IR. The second class of lidar systems requires miniatur laser

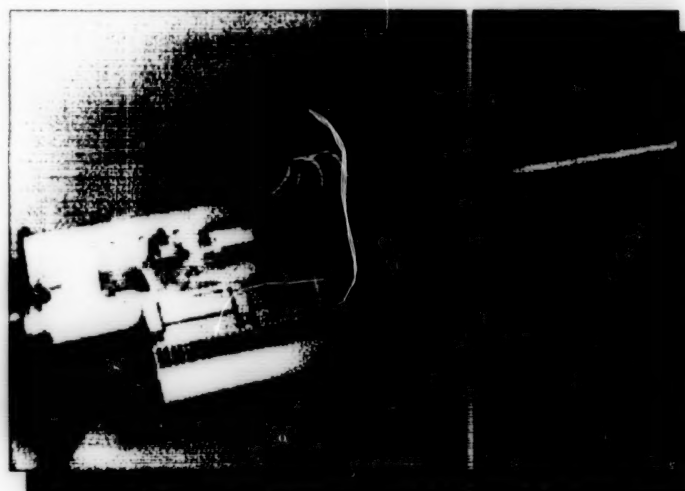


FIGURE 4.3-3. SOLID-STATE LASER TRANSMITTER

transmitters with greater than 20-percent wall plug efficiency, 0.1- to 10-microjoule energy/pulse, 1- to 10-picometer wavelength stability, 1- to 10-nanosecond pulse widths, and 1- to 5-kilohertz pulse repetition rates. High-speed, low-noise photomultiplier tubes and avalanche photodiodes in the visible and near-IR and signal processing electronics are being developed for return signal detection.

Another type of active measurement is the use of local illumination provided by tunable diode lasers for in situ absorption, luminescence or scattering measurements of atmospheric and surface chemistry, and other parameters, such as local wind speed or the water content of planetary minerals. A microlidar system incorporating a code-modulated transmitter laser of 100 to 200 milliwatts can be used to extend wind and opacity profiles up through the entire atmospheric boundary layer.

Active microwave instruments are also an important tool for remote sensing. However, they are particularly energy demanding, and low-power, low-mass options for sources and electronics are sought. Significant advances in efficiency and sensitivity are required before radars can be considered feasible for missions extending beyond near-Earth orbit. Thin-film antenna electronics for implementation on deployable structures are also important. In the future, better signal extraction will be obtained through multiple-beam antennas and more sophisticated synthetic beam patterning possible with advanced electronic beam steering.

Integrated Payloads. Highly capable microelectronics and microspacecraft systems, by virtue of their broad applicability and potential for reducing mission costs and development times, enable missions that would otherwise be prohibitively expensive (Figure 4.3-4). However, without concomitant reductions in the size and mass of the payload instruments, and their ability to be integrated into these systems, the science return of these missions would be limited.

Emerging chip-level sensor technologies offer the realization of this paradigm. Many of these opportunities are based on MEMS technology discussed under Section 4.1. Sensors of interest include fields and particles instruments, chemical and biological sensors, linear acceleration and rotational motion sensors, and meteorological sensors—in general, any point measurement that

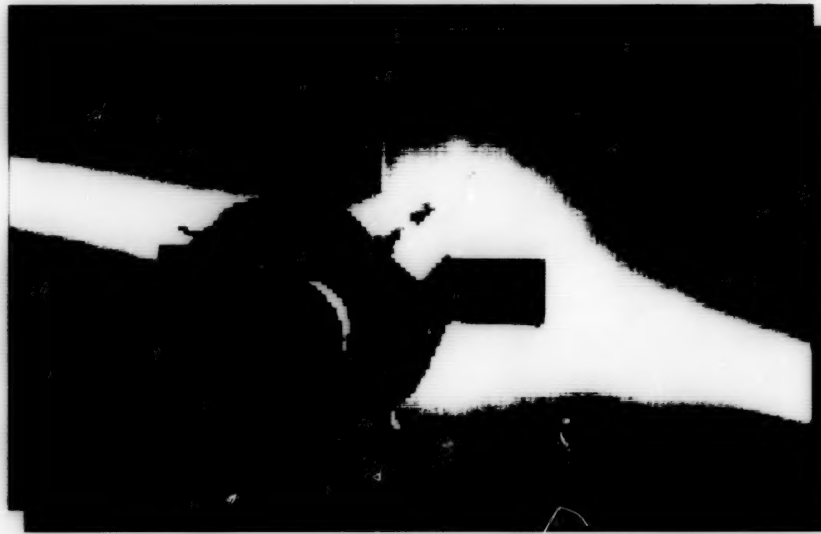


FIGURE 4.3-4. HIGHLY INTEGRATED "SENSORCRAFT"

does not require a large collection aperture for sensitivity may be a candidate for MEMS miniaturization.

Architectures encompassing multiple functions in a single system are also being explored. For example, a single optical system can be designed to serve multimission functions, including science imaging, navigation imaging, optical communications, and/or solar power collection. The extension of this multiplexing approach to chip-level systems and the strategy for moving toward fully integrated microspacecraft are discussed in more detail in Section 4.1.

Pacing Technical Issues

Progress in developing the technologies discussed above is typically governed by one or more pacing technical issues. These are technical problems that must be resolved for these items to be utilized fully in the development of compact sensors and instruments. Some examples of the desired technologies and their current technical issues are listed in Table 4.3-1.

TABLE 4.3-1. EXAMPLES OF DESIRED TECHNOLOGIES

<i>Key Technologies</i>	<i>Current Technical Issues</i>
Receivers/Detector Systems	<ul style="list-style-type: none"> Materials uniformity and process control, both of which directly impact yield cost and chip-level integration of sensor and processing electronics
Compact Instrument Architectures	<ul style="list-style-type: none"> New remote-sensing techniques and mechanisms (both passive and active) to maintain rigidity/shape in post launch environments
Active Sensor Systems	<ul style="list-style-type: none"> High-efficiency power conversion systems
Integrated Payloads	<ul style="list-style-type: none"> Development of interchangeable standardized chip sets that combine multiple functions and are usable in space environments

Other Activities

In many cases, the driving needs for the Department of Defense and NASA converge, and NASA can benefit from the investments being made by other agencies. For example, the Defense Department investment in the development of CCD technology and HgCdTe and InSb IR arrays for space-based surveillance has benefited NASA science investigations considerably. Over the past decade, BMDO has been the primary source of funding for space-based sensor development across the visible, IR, and radio frequency regimes. However, this support has been drastically curtailed in recent years, as the charter of BMDO (formerly the Strategic Defense Initiative Office) has evolved to focus on ground-based systems.

At the current time, the U.S. military forces and the National Reconnaissance Office are the primary Government supporters of advanced sensors and instruments for airborne and spaceborne platforms. The Army has consistently led Defense Department efforts in enhanced night vision, and it is currently supporting work on quantum-well infrared photodetectors, advanced mercury-cadmium-tellurium materials, and integrated micro-optics. Hyperspectral imaging is being pursued by the Navy to augment the understanding of coastal ocean characteristics and by the Air Force to detect and identify hostile targets. The National Reconnaissance Office is supporting the development of advanced space-based surveillance and reconnaissance systems. BMDO continues to support some advanced sensor system development for ground-based implementations. The Department of Energy and the Environmental Protection Agency are also involved in remote imaging and in situ chemical measurement, with the primary application of waste site hazards detection and mitigation.

Both the Air Force and the Army are supporting the development of lasers for lidar and lidar applications. The Air Force leads the work on high-power lasers and amplifiers for target and hazard detection and motion sensing, as well as the profiling of atmospheric winds. The Army is developing antimony-based laser diodes for amplitude-modulated radar and technologies and systems for millimeter-wave, ultrawideband, and synthetic aperture radars. The Air Force focus is on foliage and ground-penetrating radars, phased-array systems, and bistatic radar detection systems in which existing radio frequency sources, such as radio and television broadcasters, provide the illumination.

In the area of microsensor systems, the Environmental Protection Agency and the Department of Energy are pursuing small in situ packages for monitoring chemical and biological hazards, and DARPA is the primary developer of integrated MEMS sensor systems. The Air Force, Army, and Navy also have small microsensor programs emphasizing unattended ground (or ocean) sensors primarily to detect enemy activity. The NSF also funds fundamental work in materials, sensor, and MEMS, primarily at universities.

These investment areas of other agencies should be monitored to avoid unnecessary duplication of effort. In particular, NASA should monitor the development of technologies for high spatial and spectral resolution imaging, passive and active remote measurements in the IR and radio frequency regions, and miniature in situ packages.

4.4 Self-Sustaining Human Support

Extended onsite human exploration and development of extraterrestrial space will lead to revealing, exciting, and unpredictable scientific discoveries, a burgeoning expansion in human knowledge, and enrichment of the human experience. Before long-duration human exploration missions to the Moon, Mars, and other solar planetary bodies can be planned, however, technologies must be developed that will enable self-sustaining operations in hostile environments far from any effective support from Earth. This section describes three groups of long-term technologies that will lay the foundation to eventually enable affordable, safe, and productive extended human operations beyond Earth orbit (see Table 4.4-1).

TABLE 4.4-1. THREE GROUPS OF TECHNOLOGIES THAT WILL LEAD TO SELF-SUSTAINING HUMAN SUPPORT

<i>Human Support Technology Areas</i>	<i>Technology Elements</i>
Human Health and Performance	<ul style="list-style-type: none"> • Health and Space Medicine • Radiation Protection • Human Factors and Crew Systems/Supplies
In Situ Resource Utilization	—
Advanced Systems and Operations	<ul style="list-style-type: none"> • Advanced Life Support • Extravehicular Activity and Surface Mobility • Habitats • Telerobotics (Telepresence) • Surface Power • Advanced Operations

Human Health and Performance



FIGURE 4.4-1. IN-SPACE HEALTH EXAMINATION

Health and Space Medicine. Human health and performance in space may be affected by a number of factors, including the effects of zero-gravity deconditioning, radiation exposure, and the effects of unexpected illnesses or accidents requiring medical treatment (Figure 4.4-1). The effects of extended exposure to zero gravity is a major NASA research activity that is based on previous Russian and American space program experiences. This activity will be significantly extended with experience to be gained on the ISS. Technology must be developed to provide effective countermeasures to the deconditioning effects of zero gravity. The space radiation

hazard to human health must be understood through multidisciplinary research into the physical, biology, and risks involved in various levels of radiation exposure. Providing adequate radiation protection for humans engaged in deep space and planetary surface exploration activities requires that materials technologies and innovative designs for spacecraft, habitats, and suits must be

investigated. Onboard medical technologies must be developed to enable essentially autonomous capabilities for the exploration crew to diagnose and treat a wide variety of potential illnesses or traumas. Examples include expert diagnostic systems, noninvasive examination and monitoring, compact and lightweight medical equipment, and extended life pharmaceuticals and blood substitutes.

Radiation Protection. The potential hazard and impact of radiation on human activities in space has been recognized for four decades. Recently, with mission duration increasing and mission planning beyond Earth orbit, the assessment of risks to humans from space radiation and the mitigation of those risks have become imperatives, with risk decisions playing a major role in future spacecraft design, mission planning, and even crew selection. Advanced spacecraft and mission design, including cost and schedule, will be driven by the decisions made regarding what is acceptable radiation risk. Quantitative assessment of risk depends on sufficient knowledge in five major areas:

1. *Environment Definition*—The three primary radiation sources in space (trapped belt radiation, solar particle events, and galactic cosmic rays) are dynamic and vary temporally, spatially, and in particle energy distribution. Environment models are constructed using empirical data. With the exception of the galactic cosmic ray model, the quality and accuracy of current models are poor. Dynamic models of the environments are not available. Predicting (forecasting) solar particle events (onset, size, and duration) with sufficient accuracy for operational decisions is not currently available.
2. *Shielding and Materials*—Adequate shielding of the incident space radiation is an effective strategy in mitigating radiation exposure. Current radiation transport codes do not sufficiently describe particle interactions within the shield material and the emerging particle distributions (species, intensity, and energy distribution) exiting the shield. Shielding materials include new materials (composites). Current shielding models are limited to simplistic geometries.
3. *Radiation Effects on Humans*—Data describing the effects of exposure of humans to ionizing radiation are limited to atomic bomb survivors. Little, if any, data exist regarding exposures of humans to space-type radiation species. The effects of exposures to the heavy ion component of galactic cosmic ray radiation are poorly understood. These data are critical to permit adequate assessment of radiation risk.
4. *Radiation Monitoring Strategies*—Efforts to predict or forecast solar particle events (onset, risetime, event size, spectral rigidity, and duration) have been unsuccessful. Some large solar particle events are not produced by solar flares, but by coronal mass ejections. The largest variations in solar particle event peak fluxes seem to be associated with interplanetary shock. Instrumentation systems (and resulting model development) are required. In addition, active instrumentation is required to provide real-time assessment of the radiation environment and resulting crew exposures.
5. *Countermeasures*—Radiation exposure countermeasures include spacecraft design, mission planning and operations, shielding, and pharmacological systems and protocols. Judicious mission planning and operations have been successfully used to limit radiation exposures. The shielding provided by the spacecraft and/or habitat is fundamentally important in limiting exposures. Shielding crew members from the high fluxes of large solar particle events can be accomplished with the pragmatic shielding design of a "safe

shelter" for crew members. Pharmacological product development is considered in its infancy, and considerable efforts are required in this technical area.

Specific goals of the radiation protection technology development are to: (1) define all aspects of the radiation environment to within ± 20 percent; (2) improve radiation transport codes and shielding geometries by a factor of two; (3) assess quantitatively the risk of radiation exposure of humans to space radiation, understand the effects of such exposures, and reduce the uncertainty of the risk assessment to a factor of three; (4) improve solar particle event forecasting to the level of predicting Earth weather; and (5) develop pragmatic shield designs and develop effective pharmacological countermeasures within 10 years.

Pacing technical issues include an accurate assessment of the risk of exposure of humans to space radiation, an understanding of the uncertainties of the estimate, and the mitigation of that risk. Dynamic environment models and solar particle event forecasting techniques are urgently needed. Countermeasure development is in its infancy. In addition, a major concern is the availability of a ground-based heavy ion accelerator for the required basic research.

Human Factors and Crew Systems/Supplies. The area of human factors and crew systems/supplies covers a broad spectrum, including human-machine interfaces, ergonomics, crew productivity, habitability, food preservation and preparation, the recycling of crew systems materials such as plastics, clothes washing/drying, repair/maintenance systems, and a host of other items. The difference between using current technologies and the development of inexpensive, low-risk, new technologies for crew systems/supplies can be responsible for a 25- to 50-percent reduction of overall mission mass and cost. This is because reductions in crew systems/supplies act as a 10-to-1 mass lever in reducing vehicle and fuel mass, as well as development cost.

Human factors and crew systems also seek to provide a safe and efficient living and working environment for the crew and—backed by expert systems, robust electronic knowledge bases, and detailed system models—to permit crew-autonomous operations so that a small, Earth-isolated crew can take on the roles now performed by multitudes of ground-based experts. To reduce mass, many of the human-machine interfaces will be moved into a synthetic computer environment in the spacecraft, viewed with head-mounted displays, and actuated via tracking systems and cyber gloves. Other new technologies must also be developed to enable human exploration missions. Currently, we have no ability to store a complete diet for the 2–3 years required by Mars missions. Shelf-life extension through completely new preservation technologies will determine whether a Mars mission is even possible. Technologies for "from-scratch" cooking and the processing of crops or other raw materials into edible foods have yet to be developed.

Furthermore, the complexity of a Mars vehicle, the long mission duration, the high probability of equipment failure, communications distances of up to 20 minutes each way, and the impossibility of resupply make an adequate intravehicular maintenance system a critical and enabling component in Mars missions. Many new technologies and advances will need to be made to reduce the mass of such a system, while guaranteeing that it can respond to contingencies, including lightweight, multipurpose tools, spare parts, hoses, wire, connectors, supplies, methods for mocking up integrated circuits, decision and expert systems, troubleshooting information storage (drawings, procedures), and so forth. Methods for in-flight training must also be developed to keep skills

sharp that may have originally been learned years before their use and to meet the unexpected, and untrained for, needs of the crew.

Pacing technical issues include:

- Body-worn interfaces that generate a deep symbiosis between human and machine, including virtual interfaces, embedded real-time intelligence with decision support and context-driven data retrieval, and natural language interfaces
- System design information capture to allow the experience of ground-based engineers and experts to be included in a near-autonomous, Earth-isolated environment
- Nonintrusive methods for monitoring individual and group performance over time to identify, warn, and correct for human performance deficits caused by the unique stresses in exploration-class missions
- Methods for the preservation of a complete diet for 3–5 years to enable a Mars mission
- Technologies for reducing, reusing, and recycling crew systems/supplies to produce massive reductions in mission mass/cost for future exploration missions

Work is under way in the area of human-machine interfaces in the academic, military, and commercial communities. Also, commercial and military applications of augmented reality/virtual interfaces, embedded real-time intelligence and decision support, and natural language interfaces are being studied.

In Situ Resource Utilization

The great explorers of Earth learned to live off the land as they ventured far and long from their own bases of support. Likewise, it is fundamental to any program of extended human presence and operation on other solar bodies that we learn how to utilize the indigenous resources that are available there. The research objectives of this area are to understand the availability and possibilities of those resources and to develop the mechanical, chemical, and biological processes and supporting technologies that will enable us to use them to support human life and operations. The chief benefits of in situ resource utilization (ISRU) are that it can reduce both the cost and the risk

of human exploration by decreasing Earth launch mass and by increasing crew access to caches of consumables.

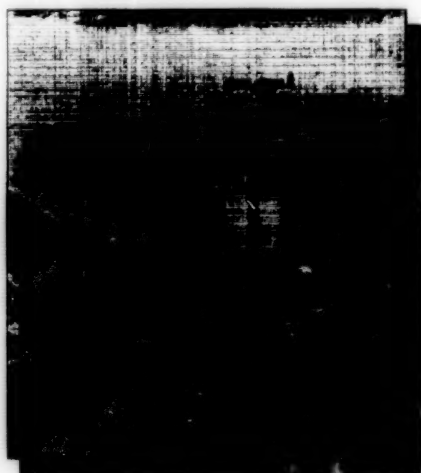


FIGURE 4.4-2. CONCEPT
OF ISCP USE

A key subset of ISRU, which in particular has significant cost and risk reduction benefits for robotic and human exploration and which requires a minimum of infrastructure, is in situ consumable production (ISCP). ISCP involves manufacturing and storing rocket propellants for surface ascent (Figure 4.4-2) and Earth return, life support gases and water for crew, and fuel cell reagents for power generation and storage. For example, systems analyses of human Mars missions have indicated that producing propellants on the surface of Mars by processing atmospheric carbon dioxide can reduce the initial mission mass required in low-Earth orbit by approximately 20 percent as compared to carrying all required return propellant to the,

Mars surface from Earth. An even greater leverage can occur for lunar and Mars missions when in situ water can be processed.

ISCP facilities can be divided into three interconnected subsystems: (1) resource collection and conditioning, (2) chemical processing, and (3) product liquefaction and storage. ISCP concepts for lunar exploration primarily consider the use of regolith (soil containing metal oxides) and, recently discovered at the lunar poles, ice. For Mars exploration, the primary feedstock initially under consideration is the atmosphere (95 percent carbon dioxide, 3 percent nitrogen, 1 percent argon), which is used to produce oxygen. Manufacturing fuels on Mars, such as methane, methanol, or other hydrocarbons, will require either Earth-supplied hydrogen or access to indigenous water resources.

Though not critical for initial human exploration, eventually sustained long-term human presence on the Moon, Mars, or other solar system bodies will require the ability to construct human base facilities using local materials. Important enabling technologies will be those associated with the extraction of local materials and conversion to plaster, fibers, plastics, glass, ceramics, and metals useful in manufacturing and construction.

Pacing technical issues include:

- *Resource Collection and Conditioning*—ISRU depends on the resources that are realistically available. Technologies for resource collection and processing on the Moon include autonomous shoveling, grinding, sorting, sifting, and separation of lunar regolith. For Mars' atmospheric resources, advanced adsorption pumps and/or mechanical compressors are required. Lunar resource collection technologies may also be applicable for Mars soil and water extraction processing.
- *Chemical Processing*—Chemical and energy efficiencies can significantly affect power requirements and Earth-supplied consumable needs. Chemical reactor technology challenges include oxygen extraction from lunar metal/nonmetal oxides, high-efficiency chemical/fuel production reactors, water and carbon dioxide electrolysis units, recirculation and boost pumps, and efficient water and gas separators.
- *Product Liquefaction and Storage*—The benefit of using ISCP depends on the cryogenic system performance. A challenge will be to minimize the mass and power associated with product liquefaction and cryogenic storage. Key areas for technology advancement include oxygen liquefaction, long-term cryogenic storage, and autonomous cryogenic fluid transfer hardware. Furthermore, because the ISCP propellants will be stored in the ascent vehicle propulsion system tanks, cryogenic storage performance will also affect ascent vehicle and propulsion system designs.
- *Survivability*—ISCP plants will be operated in incredibly harsh environments without maintenance, so components must be both robust and long lived. ISCP hardware will need to demonstrate lifetime capabilities not currently found in terrestrial chemical production plants. Also, because many ISCP processes operate at high temperatures with regular, diurnal cycling, the development and selection of new materials will be important.
- *Autonomous Operation*—If ISCP facilities are predeployed to a planetary surface, human crews will not be available to control the operations directly. Communications time delays, particularly for Mars operations, necessitate that the facilities must be able to operate autonomously with built-in failure detection and recovery capabilities. This is a major

concern, even for terrestrial petrochemical plant operations. Technology challenges include highly reliable sensors, advanced simulation and modeling software, and the development of flexible control and failure detection, isolation, and recovery software.

Related work is under way within the Departments of Defense and Energy. Millions of dollars have been spent on developing technology for these programs that can be leveraged.

Advanced Systems and Operations

Extremely reliable, long-life, robust, self-diagnosing, self-reconfiguring, and self-maintaining systems are the visionary goal for the systems that will support long-duration human operations in deep space. Technologies must be developed that enable lightweight, extremely reliable regenerative life support capability (i.e., systems that regenerate air and water and other consumables by processing and reconstituting waste products). Robotic assistants and mobility aids must be developed to make human operations safe and to make their scientific investigations productive. Intelligent expert systems will be needed to assist the crew when the base is attended and to manage operations with minimal remote assistance from Earth during periods in which the onsite crew is absent.

Advanced Life Support. It is imperative that life support systems operate with increased autonomy and minimize consumables for considerations of both safety and cost and to ensure crew health. Using advanced life support technologies provides this autonomy and increases productivity of the mission by reducing the mass, power, and volume necessary for human support, thus permitting larger payloads for science and exploration. Two basic classes of life support systems must be developed—those directed toward applications on a transportation/habitation vehicle and those directed toward applications on the planetary surfaces. In general, it can be viewed as those systems compatible with microgravity and those compatible with hypogravity environments. The technical objectives of advanced life support are as follows:

- Provide technologies that significantly reduce life-cycle costs, improve operational performance, promote self-sufficiency, and minimize the expenditure of resources for missions of long duration; specific goals are to:
 - Fully close air and water loops to eliminate expendables
 - Develop and integrate resource recycling/processing and contaminant control systems to increase self-sufficiency
 - Optimize food loop closure with concomitant air and water revitalization based on the growth of crop plants
 - Provide efficient, reliable active thermal control (heat acquisition, transport, and rejection)
 - Develop fully regenerative integrated systems technologies that provide air, water, food, and resource recovery from waste
- Resolve issues of microgravity and hypogravity (reduced gravity) performance through space flight research and evaluation; specific goals are to:
 - Develop predictive models of fluid and fluid/gas behavior and interactions in reduced gravity that can be used as a basis for the design of new hardware

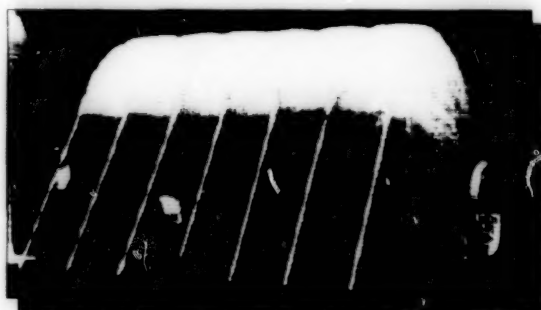
- Achieve equivalent productivity, control, and predictability of bioregenerative life support components in microgravity as on Earth, and characterize the performance of bioregenerative systems at lunar and Martian gravities
- Demonstrate reduced gravity performance of gravity-sensitive life support hardware components and subsystems

The pacing life support technical issues are to improve biological water processing effectiveness in microgravity, the recovery of resources from solid wastes, food processing from plants grown onsite, the long-term preservation (more than 3 years) of food, and the minimization of power and thermal rejection requirements for plant growth (from approximately 100 kilowatts per person to about 20 kilowatts per person). Related work is under way in a variety of other Government and industry programs addressing water recovery, crop breeding, control, and monitoring and automation.

Extravehicular Activity and Mobility. Extended human operations on the ISS will require a significant amount of extravehicular activity (EVA) tasks during the assembly and operational phase of the project. The experience gained during these extensive EVA's will contribute greatly to the design changes that will occur in more advanced EVA systems that will take humans to the surface of Mars. More comfortable, lighter weight suits will be the goal for this new design. The goal is to increase greatly the mobility of the EVA suits and increase the EVA sortie capability from 8 hours to 12 hours, while simultaneously reducing the mass of the suit by one-third. These refinements will be added without risking the primary purpose of the EVA system, which is to sustain an astronaut's life in the harsh environment outside of a spacecraft.

The typical transit time for an Earth-to-Mars mission is 150-200 days. Because this extended time in zero gravity will contribute to bone and muscle loss in the crew members, it cannot be expected that these astronauts will have the capacity to walk great distances easily upon their arrival at Mars. Therefore, a plan is in place to develop robotic technologies that will assist EVA crew members in their traverses across the Martian surface. These technologies range from small, autonomous "tool caddies" to large, pressurized four-wheeled rovers, with the capacity to provide life support for up to four crew members and a range of hundreds of kilometers beyond the main landing site.

Pacing technical issues for this area include a regenerable carbon dioxide removal system that does not require the use of any consumables, a suit cooling system that does not use water as a consumable, and a portable life support system (breathing system) for Mars that utilizes in-situ-produced cryogenic oxygen. In a related external activity, several proprietary industry concepts for carbon dioxide removal systems are currently under development.



Habitats. Space and planetary surface habitats are pressure vessels that provide the living quarters and support systems needed by human crews engaged in space exploration (Figure 4.4-3). Structural and materials research and technology development is required for the very lightweight and comfortable habitats needed for the months of

FIGURE 4.4-3. HABITAT CONCEPT

transport to Mars and for the months, and possibly years, that humans will spend on the surface of the Moon or Mars carrying out exploration and development activities. Such habitat technology is also important because it has the potential to open up the possibilities for near-Earth-orbital platforms for commercial usage. Major technology interests are in advanced lightweight materials, the use of inflatable design techniques, and techniques for providing protection from micrometeoroids, orbital debris, and radiation protection. Related activities are under way within several other Government agencies.

Telerobotics (Telepresence). Telerobotics technologies have proven to be tremendous magnifiers of human space exploration efforts to date and are expected to play an even more essential role in future missions. The use of remote manipulator arms on the Space Shuttle, the planned use of similar arms, the additional functionality of dexterous manipulators in the assembly and maintenance of the ISS, the recent demonstration of a free-flying inspection robot from the Shuttle, and the spectacular successes of the telepresence-operated Sojourner robotic rover, which landed on Mars in July 1997, are all harbingers of the role that robotics and telerobotics will play in supporting future human space exploration. Many of the surface systems required for human missions to Mars will be telerobotically deployed, checked out, and operated years before the human crews arrive. Crews on the surface of Mars will telerobotically control remote rovers and remote sampling equipment. Crew robotic assistants will assist in the operation and maintenance of the surface base systems.

Goals for telerobotics technology include developing and demonstrating improved remote sensing, inspection, and manipulation that will lead to increasing the operational capability, safety, cost-effectiveness, and probability of success of NASA missions. Quantitatively, this telerobotic capability would enable a minimum of 50 percent of the required extravehicular work required in orbit and on planetary surfaces by the year 2004 to be performed by telerobotic means. The functions provided include on-orbit inspection, assembly and construction, processing, servicing, repair, and defense. Planetary surface applications include exploration, construction, site preparation for human presence, processing, servicing, and repair.

A specific near-term goal has been set to produce a lightweight (< 1 kilogram), low-cost (less than \$500,000), highly autonomous EVA robotic camera that can operationally "roam" and stationkeep about orbiting (or interplanetary) platforms at a separation distance of 1 inch to 1 mile. A second midterm goal is the development of a space robot EVA associate/surrogate with human-in-a-suit perception and dexterity performance with 50-percent life-cycle cost of the current ISS baseline. A longer term vision is the development of technologies that will enable affordable, coordinated robots that can deploy, assemble, and construct laboratories, habitats, and facilities in orbit and on planetary surfaces.

Pacing technical issues for telerobotics include increasingly reliable and higher performance on-orbit and planetary surface mobility, perception, and dexterity with greater navigational accuracy between the robot and the workspace while reducing flight weight, and operational cost. Related work in terrestrial robotics is under way at the Departments of Energy and Defense. Canada, Japan, Europe, and Russia are also supporting related activities.



FIGURE 4.4-4. SURFACE POWER SYSTEM
CONCEPT

Surface Power. Planetary surface power systems (Figure 4.4-4) are required for human base operations, human surface exploration operations, drilling and mining operations, and ISRU. Base power requirements may range from 25 kilowatts for a typical lunar exploration base up to 160 kilowatts for a typical Mars surface exploration base.

Advanced power system technologies are critical to developing an affordable approach to supporting human life and operations while in transit to and on the surface of other

solar bodies. Power systems must be very lightweight, extremely reliable, and able to operate for years without significant human maintenance. Example technologies that are being considered are advanced highly efficient and lightweight solar photovoltaic systems, thermoelectric conversion, regenerative fuel cells for energy storage, fuels extracted from planetary resources, and nuclear reactor systems. In general, solar technologies are mass and volume competitive at the lower power levels, while nuclear systems scale more favorably with higher power levels.

Many power system technologies are important for both robotic space exploration and human space exploration. Robotic missions can be a "proving ground" for the larger, more robust systems required for humans. Also, many of these technologies are directly applicable to the commercial aerospace sector in which large infrastructures of Earth-orbiting satellites will provide real-time global communications and information access. For example, recent improvements in photovoltaic cells and batteries have greatly benefited Earth-orbiting commercial missions by extending satellite lifetimes and increasing payload capability. Some specific goals for advanced power technologies are listed in Table 4.4-2.

TABLE 4.4-2. GOALS FOR ADVANCED POWER TECHNOLOGIES

<i>Technology</i>	<i>Goal</i>
Fuel Cells	<ul style="list-style-type: none"> • 20,000-hour life • Greater than 400 watt-hours per kilogram
Photovoltaics	<ul style="list-style-type: none"> • 30-percent efficiency • 300 watts per kilogram • Large, deployable structures
Energy Conversion	<ul style="list-style-type: none"> • Greater than 25-percent Brayton • Greater than 15-percent static conversion
Power Management	<ul style="list-style-type: none"> • Greater than 2,000 volts (DC/AC) distribution and control
Reactors	<ul style="list-style-type: none"> • Greater than 25 watts per kilogram (system level)

Pacing technical issues include reactor power system components, high-density/long-lived energy storage, and high-efficiency, low-mass solar arrays. Related activities are under way within the Department of Defense in solar cells, batteries, and power management, and the Department of Energy is supporting efforts in high-efficiency thermal-to-electric conversion. Work is under way in Russia on high-temperature reactor fuels for bimodal power and propulsion systems.

Advanced Operations. Self-sustained long-duration human operations in deep space will require a new paradigm for vehicle systems and subsystems design—a culture shift in ground and onboard operational techniques, and the development of new innovative/enabling operational tools to be both cost-effective and safe. Focus will be placed on vehicle and ground systems technology developments that will require minimal human operational intervention in use. This will drive operations costs down and should improve safety. Vehicle systems technology developments, which are extremely reliable and modular, offer long service life, are self-diagnosing and self-repairing, and require little to no real-time ground or onboard human attention across the crewed programs. This paradigm will be applied to resource-providing systems, transportation systems, teleoperated systems, life support systems, EVA systems, communications systems, etc.

Operational support capabilities based on cutting-edge information systems technologies will be required to enable the reduction in real-time, around-the-clock ground support and training (operations costs) and/or to reduce flight crew required attention to maintenance, monitoring, training, and planning (more time for science). This technology area will draw heavily on enabling tools developed in intelligent systems, the intelligent synthesis environment, and the deep space systems technology areas.

Ground flight control techniques will be required to change to make long-duration, long-distance missions affordable. Minimal flight control ground support will be the target. Distributed payload/science/biomedical operations is envisioned. Control centers may be a thing of the past as connectivity-enabling technologies will allow for communications capabilities that downplay the perceived team need for physical proximity. Near-Earth flight crews could provide their own flight day planning and vehicle resource management with only minimal effort. Management action teams composed of subsystem managers and flight dynamics, payload, science, biomedical, and even flight crews could form “virtually.” The average civilian could log on to the vehicle web site and be placed “virtually” in space or on a remote planet.

As new techniques, tools, and systems are developed for use in deep space crewed missions, they can be tested using existing space assets. The Space Shuttle and ISS are prime testing grounds for developing, testing, and certifying the new and revolutionary operational techniques, tools, and systems.

Pacing technical issues include the following:

- Requirements for automated vehicle and crew health monitoring, fault detection/prediction, and action recommendations
- Fully automated guidance, navigation, and control
- The development of onboard planning/scheduling systems that provide ease of use and autonomous flight crew planning operations

- Spacecraft and habitat-based training tools with embedded training instructor capabilities required for systems, science, biomedical, and flight control operations tasks
- Robust telepresence systems
- High-definition television across low-bandwidth networks
- High-data-rate deep space communications links
- Virtual reality force feedback systems
- Wearable, high-speed, and low-battery-consumption computer systems
- Space/ground network standards—interoperability

4.5 Deep Space Systems



FIGURE 4.5-1. HOSTILE ENVIRONMENTS OF SPACE

While space offers the potential of answering the fundamental scientific questions at the very core of human curiosity, the space environment is also very hostile and unforgiving (see Figure 4.5-1). Besides operating at extremes in terms of temperature, pressure, and radiation, there is a particular set of formidable issues associated with operations at extreme distances from Earth and, in some cases, the Sun.

These “deep space” missions challenge the basic physics of propulsion systems needed to cover astronomical distances—power systems that must function when the Sun appears no brighter than some stars, communications systems that must convey high data rates across vast distances using virtually no power, and sufficient onboard intelligence and autonomy to phone home only to deliver new insights.

These ambitious, robotic, long-lived missions, designed and executed at the limit of the technically possible, extend human reach to both the very center and beyond the edges of the solar system.

When we look 40 or 50 years into the future, we see a time when the Origins program will have borne fruit and identified those star systems among the thousand stars nearest the Sun having a planet hospitable to life. A robotic probe to that star system will be a natural next step for the space program. Such a mission will be far from an extrapolation of today’s planetary missions. An interstellar probe will require the application of physical processes we cannot today employ in such disciplines as propulsion, communications, power, computing, and autonomy. Even the pursuit of such technology advances will revolutionize planetary exploration and enable science return from interstellar precursors missions not possible today.

This section describes the technology necessary for deep space missions primarily managed by the Space Science Enterprise. Deep space missions provide both a technological challenge and an exciting opportunity for NASA. The challenge arises because the frequent, affordable missions contemplated by the Space Science Enterprise and delineated during the recent science planning meeting at Breckenridge, Colorado, depend on the use of small, inexpensive launch vehicles and small, sophisticated robotic spacecraft. The technological capability to produce such spacecraft

does not exist today. The opportunity surfaces because meeting this challenge will establish a technical capability to produce small, affordable spacecraft subsystems that will revolutionize the design of military and civilian Earth satellites, providing unequalled national capability.

The Deep-Space Systems Technology Plan will address the principal disciplines and describe the capabilities needed to allow the vision of future space science to be realized, spanning the development spectrum from research to demonstration as appropriate. Only the highest priority advances are described, and it is assumed that advances being pursued in the interest of commercial and military satellites that benefit deep space missions will be assimilated into the repertoire of capabilities available to designers of deep space missions and spacecraft. Furthermore, the implementation of the Deep-Space Systems Technology Plan will take advantage of the best capabilities to be found within NASA, academia, the Department of Defense, and industry.

Deep space systems technologies fall into the following four areas: power, propulsion, communications, and robotics. Several additional technologies are identified that may be required for specific classes of deep space missions.

Deep Space Electric Power Technology

The generation, storage, and management of electric power for deep space missions present many unique challenges and requirements. Operations in extreme temperature and radiation environments are major mission drivers. Power generation options, in particular, heavily depend on proximity to or availability of solar energy. In addition, the need to rendezvous, enter atmospheres, descend, and land and operate on or below the surfaces of planets, moons, and small bodies results in requirements for high-impact resistance, resilience to dust or particulates and atmospheric gases, or special thermal management techniques.

Power Generation. Power generation may be accomplished by converting solar energy at distances up to and perhaps somewhat beyond 2 astronomical units (AU). However, at significantly greater distances, spacecraft will have to rely on the conversion of thermal energy from onboard nuclear sources for power.

The goal for solar photovoltaics is to enable the use of photovoltaics over the widest possible distances from the Sun and as many landed planetary/small body sites as possible. To do this, technology developments are needed in several areas, as follows:

1. Lightweight solar arrays (greater than 100 watts per kilogram) are essential to the utilization of solar photovoltaics at great distances from the Sun (greater than 2 AU). Such distances will require large collection areas; thus thin-film solar cells along with ultralight deployment structures, including inflatables, will be needed to minimize launch masses.
2. High-efficiency solar cell technologies (greater than 25 percent) are being rapidly developed by industry. However, high-efficiency solar cells must be developed with radiation resistance for missions near Jupiter or the Sun, with the capability of nondegraded performance under low solar intensity and low-temperature conditions at great distances from the Sun (such as 2 AU). For surface power generation, low-light and low-temperature conditions similar to those experienced in deep space may be experienced in planetary regions, even near the Sun (such as in polar regions).

3. Special photovoltaic system technologies may also enable the wider use of solar energy. Concentrator optics may expand the use of high-efficiency solar cells to well beyond the asteroid belts (≥ 2 AU). Also, substantial technology development is needed to provide the high-temperature components necessary for the operation of solar arrays near the Sun.

Small planetary surface nuclear power generation systems will be required as precursors to larger systems to be used for eventual human exploration of the planets.

The goal for thermal-to-electric conversion from radioisotope/nuclear power sources is to enable the efficient use of nuclear fuel for deep space missions when the solar flux is insufficient for solar operations, including planetary surface and subsurface activities. Technology needs in this area include the following:

1. Static thermal-to-electric technologies, such as alkali metal thermoelectric conversion, thermophotovoltaics, or advanced thermoelectrics, offer higher efficiencies with no moving mechanical parts. Quiet, long-life operation is the payoff for power sources in the range of a few hundred watts (alkali metal thermoelectric conversion and thermophotovoltaics, near 20-percent efficiency) down to ultralow, milliwatt power sources using thermoelectrics.
2. Dynamic thermal-to-electric technologies, such as Stirling and Brayton cycle engines, may also play a role in nuclear power sources when the effects of moving parts are not a factor or can be minimized. They may be used in applications from a few watts (Stirling) to many kilowatts (Stirling and Brayton). Dynamic conversion is typically considered enabling for large, reactor-based surface power systems in the hundreds-of-kilowatts class or greater. They both offer high efficiencies (from the teens to more than 20 percent) in their applicable power ranges.

Energy Storage. Energy storage systems may be needed for primary power or for operations during some phases or cycles of specific missions when power generation is inadequate (such as nighttime periods, eclipses, low-temperature environments, and so on). The goal is rugged, high-energy density, rechargeable electrochemical energy storage systems to enable planetary orbital and landed solar-powered missions.

Low-temperature rechargeable batteries capable of operation down to -80 degrees Celsius are needed for Mars and other planetary missions, with stored energy densities near 100 watt-hours per kilogram. Thousands of cycles will eventually be needed for deep space applications. High-impact rechargeable batteries capable of operation down to -80 degrees Celsius and capable of operation after hard impact (up to g's in the ten thousands) are needed for penetrators on planetary/small body surfaces. Regenerative fuel cells are needed for energy storage on the lunar or Mars surface in connection with large solar power generation systems. Such systems, usually in the tens-of-kilowatts range, are considered enabling for initial operating capabilities for permanent human settlement of the Moon and Mars.

Power and Thermal Management. Power (and thermal) management system technologies are needed to provide the power electronics and thermal management systems that will enable power

system functionality in extreme deep space environments. Low-temperature power electronics are needed for the low-temperature extremes of deep space and on planetary surfaces. Electronics may be required to function at temperatures below -100 degrees Celsius or lower. High-temperature power electronics are needed for the high-temperature extremes found near the Sun and on Mercury and Venus. Temperatures may exceed several hundred degrees Celsius. Thermal protection coatings, materials, and devices may be needed for special applications, such as flight near the Sun or atmospheric entry, and electromagnetic shielding for plasma arcing mitigation may also be needed for specific missions.

Deep Space Propulsion

Propulsion has become one of the dominant mass elements of deep space robotic spacecraft for two reasons. First, deep space missions are becoming more difficult from a propulsion point of view. While robotic spacecraft would once fly past planetary bodies of interest, today's missions seek to rendezvous with, orbit, land on, or even return samples from these bodies. As deep space missions are more ambitious propulsively, the mass of the propulsion system increases as well, because the mass of at least part of the "dry" propulsion system is proportional to the mass of the propellant to be consumed. The proportion of the spacecraft that is devoted to propulsion components also increases as electronics systems become more mass efficient. The orders-of-magnitude increase in avionics capability that has been accompanied by an orders-of-magnitude decrease in the mass of avionics systems has not only made spacecraft more capable, but these trends have also lowered the dry mass of the spacecraft. This trend is easily seen in the ratio of dry propulsion mass to the dry mass of the spacecraft, which has increased from 10 percent for Viking to 11 percent for Galileo in 1989 to 19 percent for Cassini in 1997 to a projected 38 percent for the Europa Orbiter in 2002.



FIGURE 4.5-2. NSTAR ION PROPULSION ENGINE UNDERGOING THERMAL VACUUM TESTING AT THE LEWIS RESEARCH CENTER

In 1993, this trend was apparent and was one of the reasons that the NASA Solar Technology Application Readiness (NSTAR) program to validate ion propulsion for deep space spacecraft was initiated (see Figure 4.5-2). By making the advantages offered by an order-of-magnitude increase in propellant efficiency available to the deep space science community, NSTAR has made possible ambitious missions to primitive bodies as part of the Discovery program.

As we now look ahead to the challenging missions identified for the Deep-Space Systems Technology Plan during the conference at Breckenridge, Colorado, it is clear that greater advances are necessary if the Breckenridge vision of frequent missions using small launch vehicles is to be realized.

Achieving that vision requires that the dry mass of propulsion systems, as a fraction of the spacecraft's dry mass, not only be held at historical levels but reduced below those levels as spacecraft become even smaller. Today, the deep space program is faced with several immediate propulsion challenges: chemical propulsion for the Mars Ascent Spacecraft, chemical propulsion for Outer Planet spacecraft, and electric propulsion for high Delta-V missions.



FIGURE 4.5-3. CONCEPT OF ASCENT PROPULSION

Mars Ascent Spacecraft. The Mars Sample Return mission planned for 2005 will be launched with a Delta-III launch vehicle (see Figure 4.5-3). The limited payload capability of the Delta-III puts enormous mass pressure on such an ambitious mission. To be successful, the dry mass of the propulsion system to be used on the Mars Ascent Spacecraft for this mission must be less than one-half that of the system that could be developed using today's state of the art. Beyond this requirement, the main rocket engine for the ascent propulsion system to optimize spacecraft acceleration must provide 600 poundsf of thrust—a thrust level for which no contemporary rocket engine is made. Furthermore, the Martian thermal environment requires a compatible propellant combination, MON-25/MMH, to minimize the thermal control penalty imposed on the spacecraft. That a rocket engine designed to use this propellant combination and to operate from an initial temperature of -40 degrees Celsius to -50 degrees Celsius does not exist today is

but another propulsion challenge to be overcome for this mission.

Outer Planet Spacecraft. Outer planet spacecraft, such as the Europa Orbiter, the Pluto-Kuiper Express, and the Solar Probe, all face a similar challenge: fitting the spacecraft needed to perform a scientifically and propulsively demanding mission onto a launch vehicle having limited launch mass capability. To meet this challenge, the dry mass of the propulsion system must be reduced by a factor of two from that which we are currently capable. This is similar to one of the challenges faced by the propulsion system for the Mars Ascent Spacecraft. Because the thrust level for the Mars Ascent Spacecraft is much larger than that of the spacecraft for the Outer Planet missions, the components developed either for the Mars or the Outer Planet applications would not be applicable directly to one another, but the design techniques and approaches developed for each would be mutually supportive.

In some instances, the Outer Planet spacecraft require precision pointing and attitude stability that cannot be achieved even with the 0.9-newton attitude control thrusters available today. In the absence of lower force thrusters, these spacecraft could only achieve the precision pointing and stability they require by using reaction wheels, which present a significant mass penalty. The development of a millinewton hydrazine thruster has been identified as a way to achieve the desired pointing and stability without incurring a mass penalty the spacecraft design cannot afford. The magnetic field and rapid rotation rate of Jupiter presents a unique opportunity for the use of

tethers as both a power-generating system and a propulsion system. Return visits to the Jovian system could benefit significantly from tethers if the technology necessary for their use is brought to fruition.

Electric Propulsion. For deep space missions, the high I_{sp} offered by electric propulsion affords significant propellant mass saving for high Delta-V missions. Because of the large variation of solar isolation experienced by deep space missions, the electric propulsion system that propels these spacecraft must have a large throttling range over which it efficiently operates, a long service life to minimize the number of units needed, and the ability to process large amounts of power to shorten trip times. An ion propulsion system derived from the NSTAR system is needed that offers increased lifetime (measured as total propellant throughput), improved low-power efficiency from an improved neutralizer, a lighter weight power processing unit, and a more efficient propellant storage and control system that allows for the independent control of each of the flows to the ion engine.

Looking farther into the future, the need for even more mass efficient systems can be seen, particularly as spacecraft become smaller. Improved ion thrusters that offer lower specific mass are needed and can only be realized from improved modeling of the fundamental physics of ion thrusters. Eventually, as spacecraft become still smaller, both chemical and electric propulsion systems of the same scale as the microspacecraft they propel will be necessary. Work today investigating MEMS-scale valves, flow controllers, and thrusters (both chemical and electric) is necessary if the propulsion systems of tomorrow will be available for the spacecraft of tomorrow to realize their potential.

If we lift our eyes to a more distant horizon, we see beyond the limits imposed by the solar system and wonder about the new things we will discover when we reach outside the orbit of Pluto to the Kuiper belt, the Oort cloud, and beyond. Such propulsion concepts as very high-power electric propulsion, antimatter catalyzed fission/fusion, fusion, or beamed energy propulsion are necessary to reach these distances in a reasonable time. When we look still farther, to a time half a century from now when the Origins program has identified star systems with potentially life-supporting planets, propulsion systems that harness a significant fraction of the energy released by matter/antimatter annihilation or capture beamed energy will be necessary for an interstellar probe to reach one of these star systems in a reasonable time. In pursuing such a long-term goal, the enormous scientific yield of precursor missions will be more readily realized.

The propulsion program that will lead to NASA's future and simultaneously address the mid-term needs of NASA's planned missions is composed of both chemical and electric propulsion, of relatively ready approaches, and of concepts whose feasibility has not yet been demonstrated. And spanning all these concepts, near and far term, is the need to reduce propulsion dry mass, which improves the performance of all propulsion approaches.

Advanced Deep Space Communications

The Space Science Enterprise section of the NASA Strategic Plan states the desire to develop a virtual presence throughout the solar system with the equivalent of a "solar-system wide area network" providing Internet-like connectivity between scientists and their spacecraft instruments.

This vision will transform what we currently call deep space communications into a terrestrial communications paradigm, with extra-solar system or interstellar communications assuming the "deep space" label. An advanced deep space communications technology program is critical to realizing this goal.

Deep space communications currently refers to any communication with or between any spacecraft (orbiter, flyby, observatory, and so on) beyond 2 million kilometers from Earth. Such communication uses an internationally agreed-on set of radio frequency bands that are set aside for deep space communications or the currently unregulated optical frequencies. As part of the deep space mission, however, there are also more localized communications (for example, over distances of 10,000 kilometers or less) necessary for in situ instruments (lander, rover, microprobe, and so on), formation flying, EVA, or other short-range communications needs. While these short-range systems may use more traditional Earthbound frequency bands, they must also operate in the harsh deep space or planetary environment. Note that no assumption is made as to whether the mission has a human pilot or is robotic. The technology portfolio covers the full end-to-end link, including all spaceborne and Earthbound assets.

A number of constraints make communications with deep space missions unique: extremely weak signals, deep space-specific frequencies, environmental extremes, and small highly integrated spacecraft (spaceborne or landed). In addition, special requirements are frequently placed on the communications signals or their transmit/receive systems to enable precise spacecraft navigation or to enable radio or optical scientific measurements of the interplanetary medium.

Deep space spacecraft operate at a distance of many millions (even billions) of kilometers from Earth, and thus when the signal from the spacecraft arrives at the receiving station on Earth, it is very weak. Closure of this communications link requires aggressive measures on the spacecraft to radiate as much effective power as possible and the very special receiving stations of the Deep Space Network. Because the communications data rate of a given system scales as the square of distance, deep space missions pose communications challenges many orders of magnitude more difficult than those facing typical Earth-orbiting spacecraft—for example, the distance-squared factor for a Neptune mission is more than 10 billion times larger than for a geostationary commercial communications satellite. Communications over interstellar distances will be even more challenging. Aggressive applications of technology on both the flight and ground sides of the link are critical in enabling communications over these large distances.

Deep space missions are allocated their own radio frequency bands because of the extremely weak signals arriving at Earth from space and the need to minimize interference from terrestrial signals that can be many orders of magnitude stronger. Deep space-specific frequencies also imply equipment that will be different from those used for terrestrial frequencies. These differences in both frequencies and in applicable environments will require, at a minimum, significant modifications to commercial products and, in many cases, whole new designs to achieve the required performance levels.



FIGURE 4.5-4. RADIATION-HARDENED MICROELECTRONIC COMMUNICATIONS COMPONENT

Deep space missions are likely to encounter a range of environmental conditions. Temperature extremes can be both very hot and very cold. Radiation effects range from relatively benign to extreme (see Figure 4.5-4). Mission lifetimes of 10 years or more are often required just to get to the target bodies, with more time required for the operational science phases. All of these factors stress the design space for the spacecraft communications equipment. Most terrestrial communications equipment is not designed to withstand these extremes.

In contrast to the trend in commercial communications satellites, deep space spacecraft are getting smaller and more highly integrated. Hence, the communications portion must shrink and be very closely tied into the overall spacecraft architecture. This will be particularly true for small space vehicles such as rovers and landers.



FIGURE 4.5-5. INFLATABLE SPACE ANTENNA AND SOLAR CONCENTRATOR

Higher Frequency Technologies. Deep space communication is moving beyond the currently used X-band (8 gigahertz) frequencies to Ka-band (32 gigahertz) and optical frequencies for the spacecraft and ground systems (Figure 4.5-5). This move is to take advantage of the physics of shorter wavelengths to decrease aperture sizes and increase the capacity of the Deep Space Network to handle the predicted larger number of future missions. The challenge is to develop not only the equipment to utilize these new frequency bands, but also the operational techniques and methodologies to handle weather and atmospheric effects (such as diversity, adaptive signal processing, adaptive optics, and adaptive resource scheduling). A representative list of important technology development goals are listed below:

- Ka-band power amplifiers must be six times more efficient than current components and have up to 10 decibels more output power.
- Optical solid-state lasers should exceed 10-percent overall power conversion efficiency (including the power required for thermal control).
- Spacecraft antennas should provide an order-of-magnitude increase in diameter (diameters of tens of meters) and hence a larger surface area, yet they should be extremely lightweight (such as inflatables).
- Lightweight optics and telescopes should be thermally stable over wide temperature ranges (such as silicon carbon and other new materials).
- Spacecraft radios should be programmable and have low mass, volume, power, and cost.

- Data compression techniques should routinely decrease image data volumes by a factor of 100, while introducing negligible image distortion.
- Error correction coding systems and algorithms for both the radio frequency and optical channels should push performance toward the fundamental channel capacity limits.
- Low-noise temperature, large-aperture ground or orbiting receiving systems (radio and optical)
- Ultrastable frequency sources for space and ground.
- Lightweight "plumbing" should exist—that is, the size and weight of amplifiers and radios are being reduced to the point where the "stuff" that connects them together will become a dominant factor
- Low mass and power consumption acquisition and tracking systems should acquire uplink optical beacons and use those beacons for precise (submicroradian) transmit beam pointing
- Efficient short-range communications should be in the 400-megahertz to 2.4-gigahertz frequencies.

Integrated Technologies. The components of deep space communications systems must be closely integrated. This is particularly true of the short-range communications needs of in situ systems that may be heavily constrained in power and volume. Telecom-on-a-chip and microelectrical-mechanical front-ends are two examples. The development of communications technology must be also closely coordinated with the development of other systems onboard the spacecraft, such as the attitude control for antenna (optical or radio frequency) pointing and avionics for onboard data handling. In the future, we may see instruments integrated with communications functions such as a telescope serving both as part of an imaging system and an optical communications receiver/transmitter.

The communications system is also an integrated part of any autonomy efforts on the ground or the spacecraft.

None of these technologies can be developed in a vacuum. End-to-end systems analysis to ascertain the appropriate trade of spacecraft and ground resources, as well as operational coordination and economies, is fundamental to providing direction to the technology development (Figure 4.5–6).



FIGURE 4.5–6. EXAMPLE OF SYSTEM ANALYSIS TOOLS FOR A NEXT GENERATION SPACE TELESCOPE

The program will leverage the activities of the commercial communications industry as much as possible. It will form strategic partnerships with industry and academia to get the "best and brightest" as well as address the deep space unique nature of our developments.

Deep Space Robotics Technology

Cutting-edge planetary robotics technologies are needed for a wide range of deep space in situ exploration and sample return missions (Figure 4.5-7). These missions will investigate and



FIGURE 4.5-7. CONCEPTUAL
PLANETARY
SURFACE ROBOTIC
VEHICLES

characterize planets, comets, and asteroid surfaces, as well as penetrate subsurfaces and atmospheres with new robotic systems. The robotics technology program creates, evaluates, and demonstrates first-of-a-kind integrated research and technology robots, in which several critical technologies are developed together to provide new system-level deep space robotics operations to planetary mission scientists and designers. Enabling robotics technologies under development include:

- Miniaturized long-range science rovers for long-range autonomous traverse on planetary surfaces and for deploying, pointing, and operating multiple science instruments from a mobile vehicle
- Fast, stowable sample return rovers to locate, reconize, pick up, and retrieve preexisting sample caches quickly and reliably back to an awaiting Earth return vehicle, embedding unique technological advances in

mechanical and thermal design using composites, local area guidance, visual object recognition, and mobility control

- Nanorover vehicles that achieve breakthroughs in size reduction, mobility, and science return through synergistic technological advances in ultraminiature brushless DC motors and controllers, robotic mechanisms for cryovac environments, navigation in microgravity, algorithms for navigation, hazard detection, and situation assessment in microgravity
- Smartly controlled micromanipulators and drilling and coring robots to acquire soil and rock samples, to inspect and handle, and to perform precise trenching, scooping, and sample containerization in deep space planetary surface missions, plus the development of cryogenic drill mechanisms for comet and asteroid sampling operations
- Subsurface explorer robots for deep penetration and in situ soil composition and chemical analysis, maneuvering in the expected regolith (for example, soil and permafrost) of planetary bodies such as Mars or comets, with the goal of demonstrating that a self-contained vehicle can reach depths much greater than the achievable with any reasonable-mass drill rig attached to a lander

The robotics program develops research and technology concepts with broad bearing on deep space planetary and lunar exploration and habitation by robotic vehicles. Primary mission application targets are within the Space Science and Human Exploration and Development of Space Enterprises. In addition to its broad relevance, the program is providing specific technological findings of particular and immediate interest to the series of Mars missions planned over the next decade and to futuristic missions to comets and asteroids. The infusion of the program's technology is being achieved through a solid fabric of relationships with planetary scientists and mission designers. The program has successfully infused its miniature rover technology into the

Mars Pathfinder Sojourner rover and its dexterous micro-arm technology into the Mars Volatile and Climate Surveyor mission. Its long-range rover and sample return rover technologies are enabling the rover flight systems to be used in the Mars 01, 03, and 05 missions planned under the NASA Mars Exploration program. Its nanorover technology has been infused into the MUSES-CN mission currently under design for launch in 2002. The NASA New Millennium Deep Space 4 mission will incorporate the program's robotic drilling and sampling technology.

Other Advanced Deep Space Technologies

In addition to the technology program areas already mentioned, other technologies may play critical roles in specific mission applications. These would include the following examples:

- Technologies for aerocapture and aeromaneuvering, such as advanced thermal materials/thermophotovoltaics, entry guidance, navigation, and control, and aerothermodynamics models
- Advanced thin-film materials for extended use in inflatable and other large membrane structures
- Environmentally hardened structures, coatings, and materials for extended use in high-radiation or severe planetary surface environments
- Advanced integrated thermal technologies, both active and passive, for spacecraft thermal control in near-Sun, extreme deep space, and planetary surface environments
- Technologies for extended deep space autonomous operation of remote constellations or fleets of spacecraft and for ultraprecision formation control
- Advanced architectures or systems technology specific to deep space missions
- Technologies for the exploration and scientific discovery of planetary systems around nearby stars, keeping in mind that the drivers for technology investments in interstellar flight are first new propulsion systems followed by revolutionary advances in communications, power, and spacecraft long-life survivable avionics

4.6 Intelligent Synthesis Environment

NASA, as a research and development agency, has a unique mission: advance and communicate scientific knowledge and understanding of Earth, the environment of space, the solar system, and the universe; explore, use, and enable the development of space for human enterprise; and research, develop, verify, and transfer advanced aeronautics, space, and related technologies to industry. To secure a vigorous, healthy, and meaningful fulfillment of this mission at costs affordable to the Nation, dramatic and revolutionary changes are required in how aerospace systems are designed, engineered, produced, operated, maintained, and disposed of and how individual space science, Earth science, and human exploration missions are synthesized.

Several factors will drive the design of future aerospace systems, including rapid prototyping (which aims at reducing design cycle and development times), affordability with an emphasis on reducing life-cycle costs, and improved performance from the insertion of new technologies. The benefits of concurrent engineering, which became popular starting in the 1980's, are many, but the techniques involved require immense human engineering effort and have limited capability for full

reliable life-cycle cost analysis, multidisciplinary integration and optimization, the bounding of uncertainties, and the collaboration of geographically dispersed diverse teams. Moreover, even with concurrent engineering, experience has shown that about 90 percent of costs are committed within the first 10 percent of the design cycle process, when very little knowledge is available about the system or mission, thereby limiting the flexibility of affordable design changes. In an attempt to eliminate the shortcomings of concurrent engineering, several Government agencies and industry programs have been devoted to simulation-based design approaches, which rely on simulating the entire life cycle (from concept development to detailed design, prototyping, qualification testing, operations, maintenance, and disposal), before committing to physical prototyping.

The intelligent synthesis environment (ISE) is a revolutionary extension of the earlier simulation-based design and concurrent engineering concepts; it will fully address NASA's needs that were not realized by concurrent engineering and simulation-based design. It will provide the technologies needed for collaborating diverse teams, especially engineering and science teams, the advanced intelligent agents required for human-centered computing, the rapid tools for near real-time simulation and design trade studies, and an implementation strategy for a national ISE program.



FIGURE 4.6-1. HOLISTIC REPRESENTATION OF SPACECRAFT CONCEPT

The ISE will be NASA's future science and engineering design, development, and operational environment, which represents a fundamental and revolutionary cultural change in engineering design and mission synthesis to enhance significantly the rapid creation of innovative, affordable products and missions. It provides the design team with a holistic representation of the product and design process throughout the entire life cycle (Figure 4.6-1). It uses a synergistic combination of leading-edge technologies to build and assemble a widely distributed, integrated collaborative virtual environment for designing, testing and prototyping aerospace systems as well as for mission synthesis. Moreover, the ISE enables

diverse science, engineering and design teams, manufacturers, suppliers, training and operations personnel, and consultants to collaborate together in the creation and operation of the aerospace system. The environment is intelligent and adaptable with respect to end-users because it is modeled after human communication that involves a coordinated and balanced blend of multisensory communicative processes (such as audio, visual, and kinesthetic) to achieve an intuitive feel for the user. The intelligent feature of the ISE implies the presence of knowledge data bases and intelligent software agents to support and augment the diverse teams using the ISE facilities, as well as to reconfigure and adapt these facilities too different applications.

Objective

The objective of the ISE is to provide NASA's future engineering and science design and development environment, which links leading-edge technologies to establish a widely distrib-

uted, integrated collaborative virtual environment for designing, testing, and prototyping aerospace systems and for synthesizing missions. This environment will provide the means to optimize the combined performance of geographically dispersed multidisciplinary expert teams and information system-based cognitive and perceptual aids in creative design and decisionmaking.



FIGURE 4.6-2. CONCEPT
OF
INTEGRATED
HUMAN/
ROBOTIC
MISSION

Consequently, diverse science and engineering teams will be able to collaborate together at a level of interaction not previously possible. For example, in the design of the Next Generation Space Telescope or an integrated human/robotic mission to Mars, scientists will be able to examine the performance of the telescope or Mars mission early in the design cycle through simulations of the science data to be collected (see Figure 4.6-2). They will be able to perform complex tradeoffs among the science requirements, spacecraft characteristics, and mission concepts in a virtual environment by geographically distributed teams. Based on these simulations, assessments of science performance can be made, and collaboratively, scientists and engineers can redesign the telescope or Mars mission on the fly, producing on-the-spot simulations of system response and predictions of cost and risk resulting from the redesign. As mission and platform design proceeds, detailed evaluations of performance, risk, and cost can then be traded off to optimize the science return at affordable cost with acceptable risk.

The result of this type of truly interactive collaboration will be a new culture bonding science and engineering and, when expanded, bonding manufacturing, operations, training, and maintenance personnel, in which all parties have a new heightened appreciation of the interactions of all disciplines in the different phases of the project.

The major technologies that provide the underpinnings of the ISE are high-capacity communications and networking, virtual product development (including visualization and effectors for manipulating and interacting with virtual products), knowledge-based engineering, computational intelligence, human-computer interaction, high-performance distributed computing, and product information management.

ISE Components

To achieve the ISE objective, three thrusts will be pursued: a research and development (R&D) thrust, a testbed thrust, and an educational/training thrust. Supporting these thrusts are five critical components of the ISE: (1) human-centered computing, (2) infrastructure for distributed collaboration, (3) rapid synthesis and simulation tools, (4) life-cycle integration and validation, and (5) cultural change in the creativity process. The first three ISE components constitute the R&D thrust, while the fourth component directly relates to the testbed thrust and the fifth directly relates to the educational/training thrust. Moreover, the three R&D components infuse the testbed thrust with revolutionary ISE-developed technologies.

Human-Centered Computing. The objective of the human-centered computing component of the ISE is to increase dramatically the productivity and expand the creativity of the engineering,

science, and technology teams by significantly enhancing the communications bandwidth among users as well as between each user and the ISE facilities. Because the computer and/or the human can take the initiative in the ISE, the interaction of humans and computers can be viewed as a mixed initiative system. Thus, the challenge of this ISE component is to match the initiatives of experts and intelligent information system characteristics so as to optimize the overall performance of humans in the ISE. This will require high levels of interaction and dynamic capability for mapping information into visual, auditory, or kinesthetic representations. Multimedia information will be presented to the user in an intuitive coordinated form. Consequently, this ISE component will join the human to the computer in the human environment rather than in the computer environment as is the case today.

The four subcomponents of the human-centered computing component of ISE—immersive and advanced interfaces, human-machine communications, intelligent agents, and human factors—are described as follows:

1. Immersive and advanced interfaces refers to virtual reality facilities that allow groups of users to be immersed in the virtual design environment, where they can create and modify their designs in real time. Such facilities include position trackers and sensing gloves, as well as visual, audio, and haptic feedback. They also include reconfigurable/adaptive interfaces based on neurological and biological signals.
2. The objective of the human-machine communications subcomponent is the development of human-intuitive communications methods. The challenge will be to create the symbolic, linguistic, and sensory means and methods for the efficient, accurate exchange of information between the human and the computer.
3. The intelligent agents subcomponent (which includes software agents and cooperative physical agents such as robots, intelligent devices, and other nonhuman agents) needs to create a high level of support for human activity that captures, conveys, synthesizes, and adapts information and knowledge to support experts and eliminate barriers to nonexperts.
4. The human factors subcomponent explores the interaction of users and the immersive virtual environment to optimize the engineering and scientific value of time spent in the ISE and to create the cognitive means and methods for efficient, seamless dynamic interaction between the human and the computer. Information systems will provide critical support for human-centered computing that depends on easy and rapid access to accurate and reliable information and knowledge.

Infrastructure for Distributed Collaboration. The objective of the infrastructure for distributed collaboration component is to provide the facilities and resources that make user geographic location completely transparent to the product-design and mission-synthesis teams. The four subcomponents—ultrafast computing concepts, high-capacity communications and networking, diverse team collaboration, and information and knowledge—are described as follows:

1. The challenge of the ultrafast computing concepts subcomponent is to enable real-time virtual presence, near real-time simulations and prototypes, and rapid end-to-end life-cycle analyses. To accomplish this, ultrafast computers, which include teraflop-scale computers (such as the three-teraflop computers planned for Department of Energy laboratories), will be utilized. In addition, new computing paradigms will be pursued. An

example of a new computing paradigm would be a distributed heterogeneous computing capability envisioned as an "information power grid" that would supply computing resources on demand much like an electrical power grid supplies electricity. Yet another example would be DNA and biological-based computers.

2. The challenge of the high-capacity communications and networking subcomponent is to remove the barriers of distance and communications bandwidth. To a large extent, high-capacity communications will be provided by the next-generation Internet and Internet 2, which should alleviate present network bandwidth constraints.
3. The long-term goal of the diverse team collaboration subcomponent is immersive telepresence, in which participants are able to interact fully in three dimensions and even exchange virtual objects with one another.
4. The challenge of the information and knowledge subcomponent is developing efficient means for storing and managing, finding and extracting, assembling, and sending massive amounts of highly diverse data and widely distributed "information products" to highly diverse, widely distributed teams.

Rapid Synthesis and Simulation Tools. The objective of the third component is to develop rapid synthesis and simulation tools that fully integrate, model, and analyze complete hardware/software system life cycles from concept creation through system disposal. These tools are essential for performing engineering and science in near real time as required by an interactive immersive virtual reality environment. They include high-fidelity rapid-modeling facilities and simulation tools for structures, aerodynamics, controls, thermal management, power, propulsion, electromagnetics, acoustics, and optics. They also include tools for mission design, cost estimating, product assurance, safety analysis, risk management, virtual manufacturing and prototyping, testing for qualification and certification, maintenance and operations, training, and life-cycle optimization.

Some of these tools will be provided by commercial computer-aided design/computer-aided modeling/computer-aided engineering systems; others will be provided by Government laboratories and academia and others through Government sponsorship. The four subcomponents—traditional deterministic and nondeterministic simulation methods, nontraditional deterministic and nondeterministic simulation methods, life-cycle simulation tools, and design synthesis methods—are described as follows:

1. The traditional deterministic and nondeterministic simulation methods subcomponent refers to those methods that are based on first principles of physics coupled with the use of empiricism where necessary. Deterministic methods ignore predictive uncertainties, whereas nondeterministic methods account for uncertainties associated with predicted system response, performance, and cost. It is critical that design uncertainty be quantified so that the impact of uncertainty on design and mission synthesis is part of the tradeoffs performed by the collaborating multidisciplinary expert teams. The challenge of this subcomponent is to enable automatic computation of total system performance, cost, and risk from idealized estimates through accurate calculations using state-of-the-art and emerging analysis methods.
2. The nontraditional deterministic and nondeterministic simulation methods are based on the principles of learning systems, such as artificial neural networks, fuzzy logic, and genetic and evolutionary algorithms. They differ from the previous subcomponent in that

they use thinking rather than calculating. These methods are also sometimes referred to as soft computing methods. Soft computing tools exploit the tolerance for imprecision and uncertainty in real aerospace vehicles and mission operations to achieve tractability, robustness, and low solution cost. The advantage of these methods is that they are amenable to extremely rapid computations that make them a prime candidate to provide near-real-time engineering and science predictions in an immersive interactive virtual reality environment. Moreover, they can play a critical role in dealing with proprietary issues arising from the use of software from the ISI industry, Government, and university partners, because they are indeed black boxes whose internal workings provide no clue as to the knowledge they contain.

3. The objective of the life-cycle simulation tools subcomponent is the development of validated software tools for virtual mission, manufacturing, assembly, operations, maintenance, repair, and disposal. The challenge is to realize full system modeling, integration, and analysis from "cradle to grave," which requires the development of real-time simulation modeling tools for manufacturing, assembly, operations, maintenance, repair, and disposal.
4. The objective of the design synthesis methods subcomponent is the development of intelligent tools that guide the selection and synthesis of all relevant experience, data, component and model reuse, legacy software, and lessons learned. The challenge of this subcomponent is to enable teams of engineers and scientists to efficiently transform diverse ideas and concepts into full life-cycle design/mission models. The creation of design synthesis methods requires the development and synthesis of knowledge bases to capture the rules representing science and engineering design processes, smart models that are object-oriented and cognizant of how they interface with other smart models, and the use of intelligent agents.

Life-Cycle Integration and Validation. This component of the ISE has as its objective the development of capability for conducting integrated, full life-cycle analysis across wide ranges of technologies and scenarios in a distributed testbed environment. This ISE component contains the testbed thrust of the program and involves the establishment of national ISE testbeds that are an essential part of the ISE vision (Figure 4.6-3). The national testbeds will be focused on specific needs of the NASA Strategic Enterprises and consist of computer hardware and software, as well as hardware that operates in a "hardware-in-the-loop" manner, including online experiments. Testbeds are distributed, reconfigurable, and accessible to geographically dispersed diverse teams, and are based on knowledge and information.

The testbeds provide a means of developing, assessing, and validating ISE technologies. Very significantly, they provide a showcase for demonstrating how state-of-the-art computational and communications facilities and tools can be used by engineering, science, manufacturing, operations, and training teams to dramatically improve productivity, enhance creativity, and foster innovation at all levels of product and mission development. The integration of all the ISE components is carried out through the national testbeds.

The life-cycle integration and validation component of ISE contains four subcomponents: engineering process assessment, integration methods, large-scale R&D applications (testbeds), and large-scale project demonstrations (testbeds).

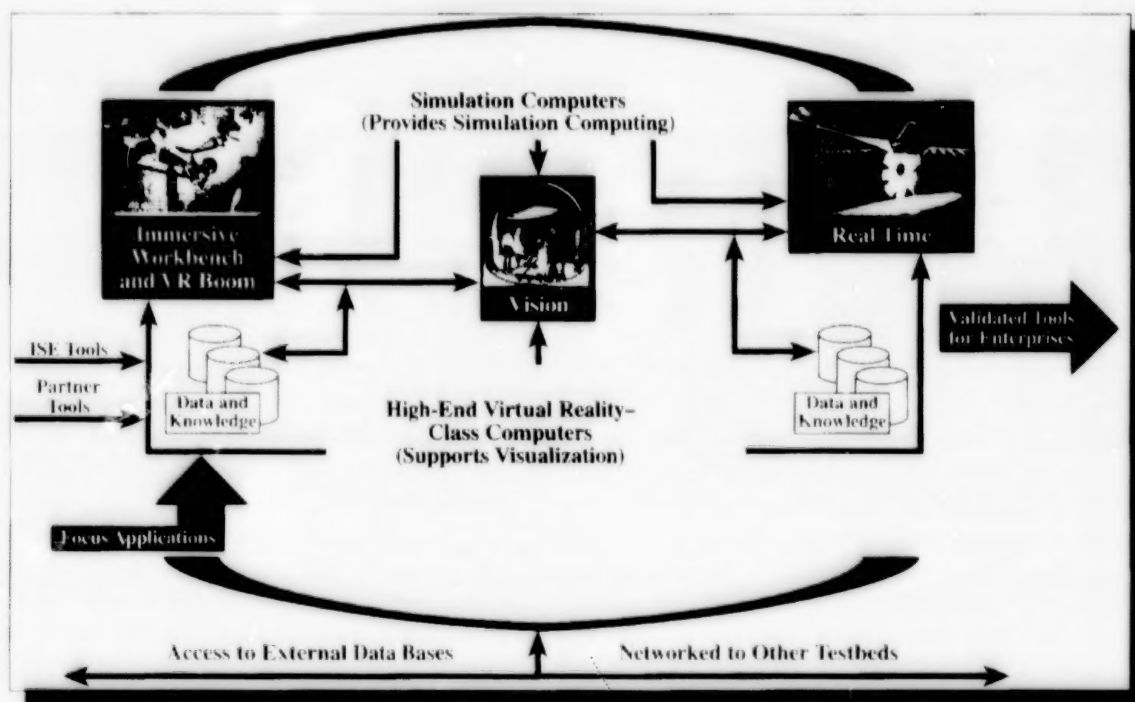


FIGURE 4.6-3. TYPICAL ISE TESTBED

1. The engineering process assessment subcomponent has the objective of identifying strengths and weaknesses of diverse engineering processes in developing life-cycle optimized products, systems, and missions. This assessment provides the quantifiable metrics for the program while indicating where further improvements and hence resources are required.
2. The integration methods subcomponent provides an intelligent "plug and play" integration capability for modularized open-architecture design systems, so that leading-edge life-cycle tools from Government laboratories, industry, and academia can be readily integrated. This "plug and play" capability will also include "hardware-in-the-loop," so that, for example, robotic planetary exploration can be integrated into mission simulations. The challenge of this ISE subcomponent is to provide real-time convergence of analysis, simulation, and testing to produce "optimal" (least-time, highest performance, lowest cost) capability to diverse collaborating teams, which requires integration methods for diverse multiple disciplines, multiphysics methods, and diverse fidelity methods.
3. The large-scale R&D applications subcomponent focuses on the validation of dramatic improvement in the engineering process and product development through large-scale R&D applications. Examples are computer-generated materials and astrobiology. This requires the assembly of testbed hardware and software, including tools from commercial vendors, industry, academia, and Government laboratories.
4. The large-scale project demonstrations subcomponent focuses on the validation of dramatic improvements in life-cycle cost, performance, schedule, and risk for next-generation science/engineering systems when applied to Strategic Enterprise project applications. Enterprise applications include, but are not limited to, Reusable Launch Vehicles, advanced telescopes, human exploration, International Space Station and Space Shuttle operations, Earth observation systems, and advanced aeronautical concepts.

Cultural Change in the Creativity Process. The ISE provides an overall framework that will lead to a revolutionary cultural change in the engineering design and certification process, and it will radically change engineering and science research in the future. The full potential of the ISE will be realized in educating and training science and engineering teams, not only in the component technologies, but also in new approaches for collaborative, distributed synthesis and virtual product development. Universities will work with industry, Government laboratories, and professional societies in developing effective instructional and training facilities for the new design approach afforded by the ISE.

Central to the ISE is the establishment of a limited number of application-focused testbeds of relevance to NASA and its customers. The national testbeds are essential to the implementation strategy of the ISE. When taken together, they provide the integration of all of the five ISE components. The national testbeds also provide the means for cooperative and joint ventures with the aerospace industry, engineering software vendors, other Government agencies, and universities. Moreover, the national testbeds provide the facilities for developing, assessing, validating, and demonstrating ISE technologies.



Possible testbed applications are Reusable Launch Vehicles, advanced aircraft and air traffic control systems, advanced telescopes such as the Next Generation Space Telescope, human and robotic planetary missions (Figure 4.6-4), and Earth observation systems. The national testbeds will form the nodes of an engineering/science technology grid linking testbed facilities.

FIGURE 4.6-4. HUMAN AND ROBOTIC
PLANETARY MISSION
CONCEPT

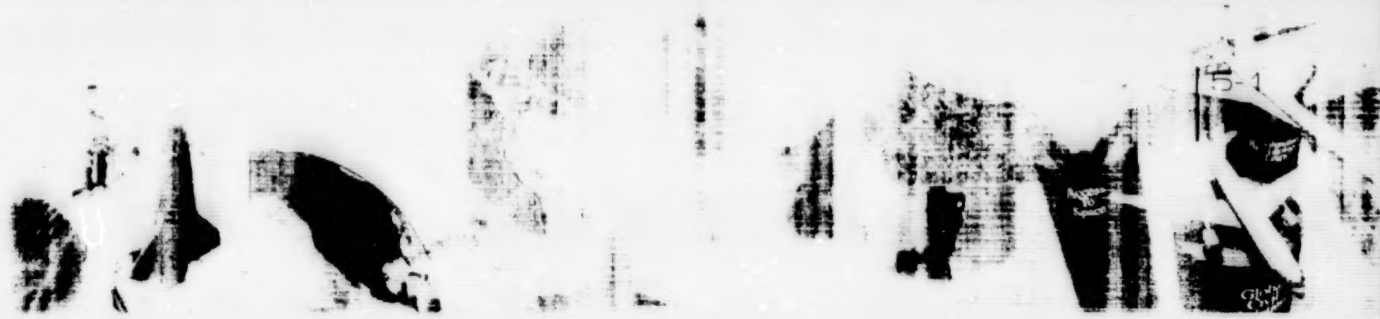
Moreover, the testbeds, when taken together, will cover all the major research issues that must be addressed to realize the full ISE vision. A number of these major research issues are:

- Determining the tools, facilities, and architectural concepts that are domain specific versus generalizable, so that tools and information systems can be shared by testbed applications wherever possible
- Identifying the visualization and interactive environments that make expert teams most effective in creativity and decisionmaking in the various phases of mission synthesis and design
- Establishing architectures for the combination of information systems (such as data bases, interpolation, and optimization methodologies) that optimally leverage the performance of diverse expert teams using multidisciplinary tool sets
- Representing and treating design uncertainty and risk so that uncertainty and risk are quantified and can be used by diverse discipline and multidiscipline expert teams with full understanding of their magnitude and impact on design and mission decisions

- Simulating effective systems, subsystems, and components, including numerical simulations at different degrees of fidelity for response, performance, risk, and cost and for manufacturing, operations, training, and maintenance
- Integrating experimental data, numerical simulations, and knowledge bases to support collaborative team creativity
- Integrating physical and predictive data into a virtual environment to achieve "hardware-in-the-loop" simulations for dramatically enhancing engineering of aerospace systems and the scientific value of space science missions
- Examining effective plug (assemble) and play (predict response, performance, cost, and risk) interactive operations in an immersive virtual reality environment in which innovative designs are easily and rapidly modeled and analytically simulated at all levels of fidelity for design tradeoff studies among geographically dispersed teams
- Studying effective large-scale applications related to project focus and research focus applications

Related Current Activities

Numerous activities are in progress in both the public and private sectors to develop improved design capabilities, drawing on the potential power of computing, networking, and collaboration technologies. In the public sector, DARPA, the Department of Defense, the Department of Energy, the National Institute of Standards and Technology, and the NSF have related activities. For example, DARPA has supported a simulation-based ship design activity. Because of the unique design challenges posed by a surface ship (for example, a very high parts count), emphasis has been placed on development of a sophisticated virtual mockup capability and on a visual programming environment with which to easily couple various design tools. The Department of the Navy has established an Acquisition Reform Office at the Deputy Assistant Secretariat level. This program is under development and focuses primarily on creating business models to be employed for doing a priori cost estimates in a simulation environment. The Department of Energy has an activity related to the ISE called Advanced Design Production Technology Initiative, the National Institute of Standards and Technology has another called System Integration for Manufacturing Applications, and the NSF has one called Knowledge and Distributed Intelligence. Within NASA, the Langley Research Center, the Ames Research Center, and the Jet Propulsion Laboratory are working jointly on an integrated design system for space applications and utilizing and extending design tools developed for potential aircraft applications by NASA. Similar capabilities are under various stages of development in support of the HEDS and Earth Science Enterprises as well.



5.0 Space Industry Sectors

In addition to the strategic technology areas described in the previous section, there is a second group of technology areas that are essential to the Agency's future and that are closely aligned with sectors of the commercial space industry. In these areas, the ability of NASA to accomplish future goals depends on the realization of substantial and in some cases revolutionary improvements in the services or products currently provided by industry. These improvements rely on investments in long-term, high-risk research and technology demonstrations that can only be achieved in partnerships that include contributions from Government, industry, and the academic community. NASA works with industry to establish goals and objectives in these areas that satisfy both Government and commercial interests. The international character of the aerospace industry demands that foreign capabilities and technologies be assessed and incorporated as appropriate, but arrangements with foreign entities are established primarily through industrial rather than intergovernmental partnerships. The four space industry sectors are:

Space Industry Sectors

Space Transportation

Commercial Communications

Commercial Remote Sensing

Space Processing

These space industry sectors align closely with the specific goals of the NASA Strategic Enterprises, so the Industry Sector Technology Plans are incorporated into the technology programs and roadmaps that are implemented by each of the Enterprises. However, because of the critical long-term components of these sectors, these plans are also reviewed by the Office of the Chief Technologist and the Technology Leadership Council to ensure that they adequately support the strategic interests of the Agency. The maturity of the space industry sectors varies widely, from well-established commercial sectors such as launch services and communications to growth and

emerging areas such as commercial remote sensing and space processing. As a result, the character of NASA's participation in these areas varies, ranging from support for specific fundamental technologies and very advanced concepts in mature areas to broader support for new applications and capabilities in emerging areas.

To ensure appropriate technology infusion into future NASA science missions, the NASA technology program will ensure that satellite bus technologies are consistent with Enterprise requirements. There are key areas, which have been developed and are still evolving, in which the commercial communications industry and NASA's science requirements are consistent. One such area that should be pursued is intersatellite crosslinks. The commercial communications industry has already demonstrated megabit-per-second radio frequency crosslinks and is now moving to gigabit-per-second optical crosslinks. The mutual development of these technologies would be a key enabling technology for Earth and space science constellations.

In addition to the established commercial industries or the emerging industries that will utilize the International Space Station (ISS), many potential future commercial space sectors have been identified. These include power generation in space for Earth, exploitation of lunar and asteroid resources, and space tourism and entertainment. In most cases, the commercial viability of these ventures depends on routine, reliable access to space, with a reduction in cost to low-Earth orbit by a factor of 10 to 100, so the space transportation technology program is pivotal to economic growth in space. A flourishing commercial space program would significantly reduce the infrastructure costs associated with space operations, as well as benefiting the U.S. economy, so NASA continues to explore new approaches to stimulating and supporting commercial space industries.

5.1 Space Transportation



"We cannot foresee the ingenuity that companies, established or entrepreneurial, will bring to the building of new industries in the 21st century based upon the Highway to Space."¹

Imagine citizens exploring, prospecting, settling, conducting business, or just experiencing space. Imagine the exhilaration of virtual reality participation in the first human landing on Mars, Europa, or Io. Imagine business parks where satellites are serviced and medicine, far superior to that made on Earth, is manufactured. Imagine movie studios where out-of-this-world effects are not just "special effects." Imagine booking your accommodations for an in-space hotel or a space cruise with an evening of stargazing with a perfect view.

¹ *Pioneering the Space Frontier (An Exciting Vision of Our Next Fifty Years in Space)*, the Report of the National Commission on Space, May 1986.

Settlements, medical research facilities, communications, tourism, fast package delivery, space-based utilities, and mining can only be imagined today. Only affordable and safe space transportation will open the "Highway to Space." This "Highway to Space" is an essential piece of the enabling infrastructure for space commerce in the 21st century. This was the case for sailing ships, with their ports and shipyards, and its impact on the New World, as it was the case for the locomotive and railroads' impact on the growth of America. More recently, airliners and the accompanying airports have enabled global commerce, just as the modern-day Internet information highway is enabling revolutionary global communications and information access. Other essential pieces of this space infrastructure—the platforms, communications, power, and utilities—will follow.

The Challenge

The National Commission on Space, in its May 1986 report, recommended "building the technology base" in three critical areas of space transportation technology to enable this "Highway to Space": "(1) significantly lowering the cost to achieve *low-Earth orbit* . . . (2) safe, reliable, low-cost transportation *in space* . . . (3) increased propulsion performance to allow higher velocity changes in space to reach *distant locations or difficult trajectories*." To better phrase the challenge, there are three critical transportation segments required to enable this "Highway to Space": (1) break cost and dependability barriers to reach low-Earth orbit; (2) break cost and dependability barriers for transportation in Earth-orbit space; and (3) break cost and dependability barriers for transportation beyond Earth orbit.

These three space transportation modes of the "Highway to Space" will require technological advances in flight systems as well as the supporting ground system elements. The three enabling technology goals presented in the subsection "Access to Space" in Section 3.4 address these three critical technology areas through the following challenges:

- Set cost-per-pound and dependability criteria and targets for the next-generation reusable launch system. The 1994 "Access to Space Study" recommended an advanced technology approach to reducing the Earth-to-orbit cost to \$1,000 per pound of payload. The all-rocket, single-stage-to-orbit concept was recommended, resulting in implementation of the X-33 program. These technologies, when demonstrated, should enable U.S. industry to reduce payload Earth-to-orbit launch costs by an order of magnitude within 10 years. Future technology developments and demonstrations are focused on an additional order-of-magnitude reduction within 20 years.
- Set cost reduction targets for Earth orbital (primary focus on geosynchronous orbit) transfer. The challenge of a reduction by a factor of 10 will focus technology development and demonstrations on reusable orbit transfer systems.
- Conduct planetary exploration missions enabled by advanced propulsion technologies to serve as pathfinders to demonstrate low-cost, high-performance systems. The first spacecraft in NASA's New Millennium program has chosen to demonstrate electrostatic (ion) propulsion. This represents a major step in validating the Enabling Technology Goal of a reduction by a factor of two to three in spacecraft propulsion system mass and travel time requirements.

Customers and Cost Thresholds

The following view of future access to space needs is based on the August 1997 "Future Space Lift Requirements Study." Four customer classes were identified for future space transportation systems. The first is a near-term (5 to 10 years) capability that includes NASA's Human Exploration and Development of Space (HEDS) Enterprise (including resupply and servicing the ISS), commercial satellites (dominated by communications satellite deployment and servicing), and small science and technology experiments. A significant cost reduction (a reduction by a factor of three from today's Expendable Launch Vehicle costs) is needed with improved reliability. Higher performance, low-cost upper stages and an orbit transfer vehicle are required to meet the overall cost goals because most destinations will be beyond low-Earth orbit.

The second customer class is the near-term (5 to 10 years) space plane or a small Reusable Launch Vehicle for military and commercial applications. A small (1,000 to 5,000 pounds) space transportation vehicle would have applications to military global access and commercial ventures, such as fast package delivery. A cost reduction of a factor of 10, high reliability, and rapid turnaround capability are keys to this customer class.

The third customer class is the long-term (15 to 20 years) need for space transportation for human exploration, including super-heavy launch, planetary transfer, and transportation to and from the planet's surface. The super-heavy (180,000 lbm) launch system will require a factor-of-10 reduction in today's expendable launch cost to deploy a human exploration mission or future large space structures, such as business parks or space utilities, affordably. A dramatic increase in space transportation system performance and safety is required to reduce cost and human trip times. Planetary ascent and descent transportation systems must be low cost and high performance to reduce propellant weight.

The fourth customer class is the long-term (15 to 20 years) spaceliner passenger service required to enable space tourism, business parks, and other visionary space industries. This transportation system will be required to approach today's airline reliability and safety with costs a factor of 100 below today's launch costs.

The study indicates that 57 percent of all visionary missions would be enabled with a cost reduction by a factor of three to 10. These missions, however, only represent 14 percent of the total payload mass. The study indicates that 86 percent of all visionary missions would be enabled with a factor-of-100 cost reduction. A super-heavy lift capability for the initial deployment of platforms and exploration would double the total mass-to-orbit potential. Figure 5.1-1 depicts the enabling attributes of future Earth-to-orbit and orbit transfer systems and associated transportation concepts.

NASA Space Transportation Mission

For more than 30 years, the United States has led the world in exploring and using space. Our National Space Policy calls for continued leadership by establishing a strong, stable, and balanced program that supports goals in national security, foreign policy, and economic growth and maintains scientific and technical excellence. The National Space Transportation Policy (PDD/NSTC-4, August 5, 1994) and the National Space Policy (PDD/NSTC-8,

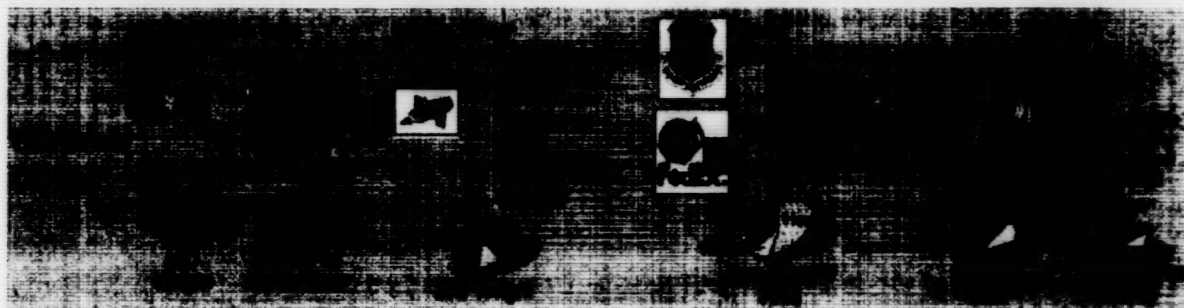


FIGURE 5.1-1. FUTURE ACCESS TO SPACE REQUIREMENTS STUDY

September 19, 1996) provide a coherent strategy for achieving these goals while supporting and strengthening the U.S. space launch capability to ensure affordable and reliable access to space. These national space policies specifically call for the following:

- Balancing efforts in the modernization of existing space transportation capabilities with investments in the development of improved future capabilities
- Maintaining a strong transportation capability and technology base for space transportation
- Reducing the cost of current systems while improving reliability, operability, responsiveness, and safety
- Developing and demonstrating technology to support a future decision on the development of next-generation transportation systems that greatly reduce cost
- Encouraging, to the fullest extent possible, the cost-effective use of commercially provided U.S. products and services
- Improving the international competitiveness of the U.S. commercial space transportation industry by actively considering commercial needs and factoring them into investment decisions

Our Nation's space program is facing a growing challenge as current launch costs consume valuable resources and limit achievements in space science, exploration, and commercial development. Many valid space missions, experiments, exploration, and commercial endeavors go unplanned because of high launch costs. To enable NASA to conduct better, faster, and cheaper programs in exploration, research, and science and to enable the U.S. commercial sector to flourish in space endeavors, significant reductions in space launch costs must be achieved.

In addition, other countries possess competitive advantages that have removed the United States from its preeminent position in worldwide commercial launch capability. The U.S. commercial space launch industry has dwindled from complete market dominance in the mid-1970's to only 30 percent of a much expanded worldwide market today. Therefore, NASA's launch vehicle needs must be balanced with commercial market interests to ensure all U.S. requirements are met.

Cost and performance improvements in current launch systems are fitting near-term measures that will moderately reduce launch costs. However, system configurations remain essentially unchanged, and long-term needs for dramatic cost reductions will not be achieved. Large reductions in launch costs require bold steps in technologies, system configurations, and business approaches. Therefore, following the guidance provided in the National Space Transportation Policy (signed by President Clinton on August 5, 1994), NASA has begun concentrated efforts to balance the maintenance of current launch systems with investments in improved technologies, with the potential to reduce future launch system costs significantly. The President's policy established NASA as the lead agency for developing reusable launch technologies aimed at future decisions regarding the development of next-generation operational systems.

Through the NASA space transportation technology programs, NASA and major U.S. aerospace companies have embarked on a partnership using innovative procurements and policy changes to permit new paradigms in launch vehicle development. Commercial needs are being addressed throughout the program life cycle and factored into the decision process at every step. In most cases, industry is in the program lead and is defining the specific tasks for Government laboratories. Specific transportation architecture needs and related technologies arise from emerging commercial industry as well as NASA science and exploration needs. These requirements form the basis for experimental flight projects and subsequently define the core supporting technologies.

The Advanced Space Transportation program (ASTP) and the Reusable Launch Vehicle flight programs—X-33, X-34, and Future-X—combine business planning and ground-based technology development with a series of flight demonstrators. These flight demonstrators incrementally expand the technology and flight test envelope, provide a realistic environment to prove reusable space transportation technologies, and demonstrate the operability required for low-cost access to space. These technology projects will provide the necessary business planning and technology verifications to permit industry and the Government to commit to revolutionary new space transportation systems beginning at the turn of the century.

The ASTP core technology program will develop and validate technologies of Technology Readiness Levels (TRL) 1 through 5, while the Reusable Launch Vehicle flight projects will extend the demonstration to TRL's 5 through 7. The underlying principle of the flight demonstrator and ASTP programs is that the Government and industry partners share in the definition and development of priority technologies leading to future new system development decisions. The role of NASA in these efforts is to promote the development of technology through TRL 7 to enable the eventual development of future launch systems. Beginning with the initial technology efforts, industry will be actively involved, from a technology and program definition perspective, to ensure a rapid transition to commercial needs at TRL 7 and above. Figure 5.1-2 shows the changing roles of Government and industry through the process of leading the eventual development of operational systems. NASA will not develop an operational launch system under the efforts described in this plan but will conduct the research and technology required for such systems. This is a unique and necessary role of NASA and other Federal agencies to ensure the long-term scientific and economic benefits of space.

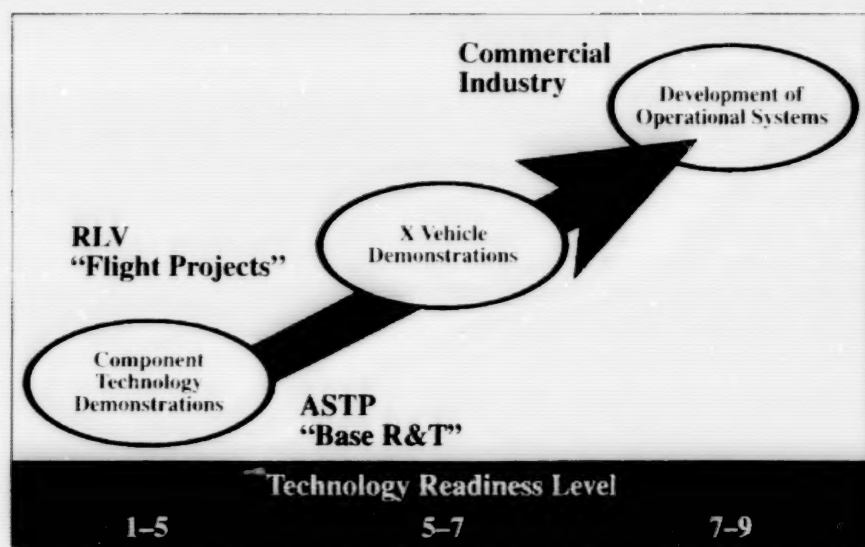


FIGURE 5.1-2. NASA'S RESEARCH AND DEVELOPMENT ROLE WILL ENABLE LOW-COST COMMERCIAL TRANSPORTATION SYSTEMS

Benefits to the Space Industry Sector

The ultimate goal of the NASA space transportation technology programs is to mature the technologies to a degree that will allow private-sector development and operation of the next-generation system. To promote this commercial goal, NASA has given industry the lead in the development of the X-33, with Government laboratories contributing critical research and development expertise and facilities. The X-33 project will complete the data set required for the Nation to evaluate the feasibility of a commercially developed and operated space launch system.

These critical technologies will be demonstrated in a combination of demonstration flight testing, to verify system performance and operability in combined environments, and parallel ground testing, to more rigorously understand individual system responses to extended life-cycle and failure mode tests. Business planning on the part of the commercial industry is equally important to the overall demonstration process.

5.2 Commercial Communications

Since the birth of the space communications industry more than three decades ago, the United States has played a predominant role in its creation and advancement. Space communications has made tremendous strides since the first NASA satellite, Echo, was launched in 1962. Today's communications satellites use increasingly sophisticated technology to provide voice, video, and data services worldwide. Much of the rapid growth and expansion of this industry can be attributed to early space communications and research sponsored by NASA and the Department of Defense.

Commercial Space Industry

The space industry is a major economic sector currently in a state of commercial expansion. Independent industry analyses have shown that in 1996 the space industry generated more than \$76 billion in revenues in the United States, with a compound annual growth rate approaching 40 percent since 1987 in many of its commercial sectors. Estimates of current annual global industry revenues exceed \$100 billion, with similarly attractive growth rates in key commercial sectors projected for the near future.

The space industry consists of those activities that depend on or relate to having a satellite or assets in orbit. The commercial satellite communications industry sector is a subset of those activities that does not include launch vehicles and services or emerging applications such as remote sensing.

Telecommunications services represent the largest sector of the space industry. Hundreds of public and private concerns worldwide own, operate, and utilize satellite systems for a variety of telecommunications services. Satellites, as an integral part of the world's telecommunications infrastructure, provide critical support for services such as long-distance telephony, television broadcasting, and cable television. In the developing world, satellites are delivering basic telephone service to millions of people for the first time. Emerging economies are using satellite technology to support rapid growth. In the United States and Europe, satellite technology is enabling new services, such as personal communications systems, distance learning, and private networks. Growth rates of 20 to 30 percent are expected to continue in many segments of this sector.

Space infrastructure includes the procurement, production, testing, and evaluation of space-related hardware and systems needed for space transportation, satellite systems, and ground facilities. Space infrastructure revenues in the United States have quadrupled in the last 10 years, and strong commercial infrastructure growth is expected to continue, principally in response to the demand for telecommunications services.

NASA. NASA is faced with a very constrained budget, and the NASA Strategic Plan directs that the limited NASA resources be focused on investments in the science and technology infrastructure. This focus is necessary for the Agency to fulfill its mandate to be a leading-edge science and technology engine. Operations services enable and facilitate the accomplishment of the research and development needed to meet this science and technology mandate. An effective operations infrastructure, with capabilities that can adapt to meet the requirements of future science and technology missions, is critical to this accomplishment. Therefore, to maximize investment in science and technology, NASA must deliver operations services that meet space mission requirements, while reducing operations costs and continuing to improve the quality of products. The strategies for doing this include using commercial services where appropriate, technology investments to enable the use of commercial assets, partnerships with industry for integrated technology development in areas of mutual interest and benefit, technology demonstrations that facilitate NASA's transition to commercial services, and technology investments for only those capabilities that are not feasible to buy.

Working Together. As NASA looks to the future, common factors in its missions are increased bandwidth requirements, increased data services to the user, and the need to reduce operations

costs. To maintain its leadership role and to be competitive, the U.S. commercial satellite industry has similar interests. Dramatic changes in system architectures and technology has postured the commercial satellite communications industry and NASA for a more symbiotic relationship in what was once a leader-follower dependence. In the near term, areas of collaboration will include interoperability issues (see Figure 5.2-1), precompetitive technology development, satellite communications workforce enhancement, and trade studies and system architecture assessments. Future challenges in advanced communications technologies, efficient spectrum use, medium Earth orbit environment-related technologies, and technologies for new frequency frontiers are prospective areas of collaboration.

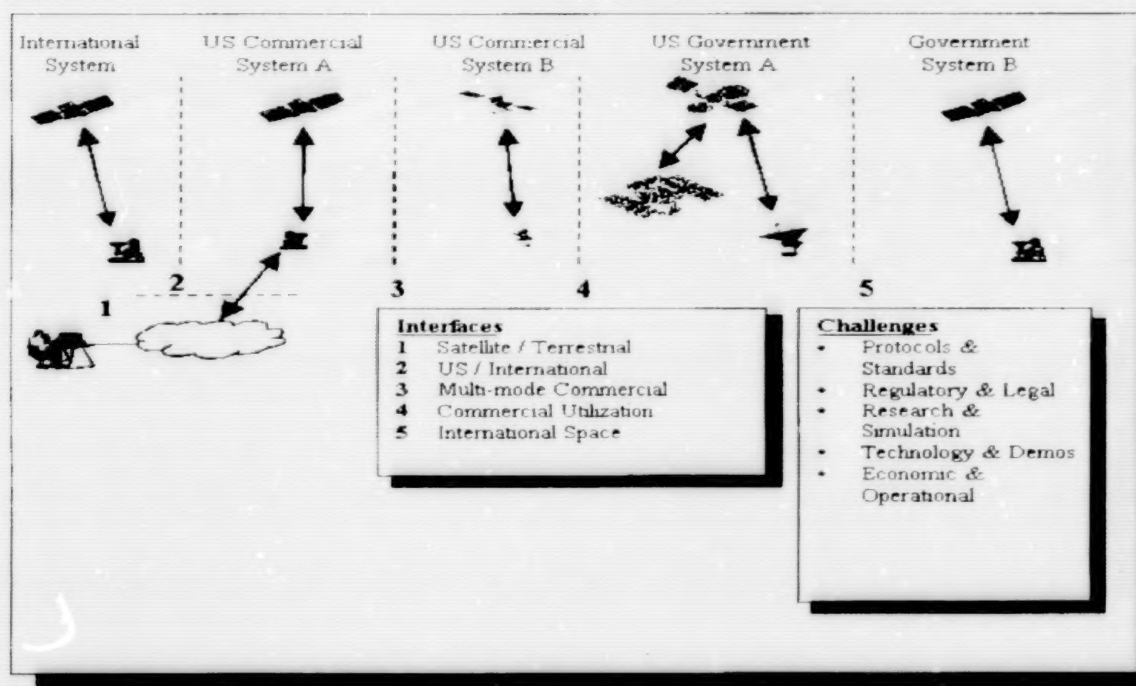


FIGURE 5.2-1. INTEROPERABILITY ISSUES

NASA's Role in the Commercial Satellite Communications Industry. The commercial satellite communications industry is an expanding market in satellite systems and services. There are 200 operational satellites today. This is estimated to grow to 1,000 by 2003 and to more than 2,000 by 2008. Satellite services are estimated to generate \$75 billion in revenues by 2005. Research and development efforts in commercial companies are approximately 10 percent of revenues, but mostly focused on the 5- to 10-year timeframe. NASA, where possible, will build on existing technology development when planning and conducting research and development. To leverage off of this multibillion dollar industry, NASA will focus the majority of its technology investment in two key areas: areas that will enable NASA's use of commercial services and assets and technologies in the 10-plus-year timeframe to act as a catalyst to open new markets for the U.S. satellite communications industry. However, specific NASA mission and Government needs that cannot be clearly met by the commercial industry must be supported also.

Critical Technology Development Areas

In 1996, a blue ribbon panel of aerospace and communications executives known as the Satellite Industry Task Force (SITF) presented its study findings on the future of U.S. satellite communications to Vice President Albert Gore. It was acknowledged that a strong research role in the field of satellite communications was appropriate for the U.S. Government during a time when satellites were entering a key stage of growth and expansion into new applications. In addition, the SITF report noted that international competitiveness was an issue and that U.S. leadership could be challenged during the crucial period of new growth and expansion. The SITF report noted several areas in which the U.S. Government should have a significant role. One of those areas was precompetitive technology development, which can be categorized into four groups: systems, payload, satellite bus, and ground segment.

Systems. The seamless integration of satellite and terrestrial communications networks is a major challenge. Seamless integration would enable universal access and reduce systems design, technology development, and network management costs. Critical technology areas include the seamless integration of satellite and terrestrial networks; systems architecture-technology assessments and tradeoffs; network management, control, and billing; modeling and simulation tools; and spectrum expansion and propagation studies.

Payload Technology. To be competitive, flexible, high-capacity satellite payloads for the National Information Infrastructure and Global Information Infrastructure are required. The SITF has set a goal of two orders-of-magnitude increase in capacity with programmability in space, time, and frequency while reducing size, weight, power, and cost. This would lead to an increased user base, new services, and a reduced cost to the user. Critical technology areas include advanced antennas, efficient power amplifiers, low-noise front-end, optical communications, onboard processors, and photonic payloads.

Satellite Bus Technology. Advanced power systems are needed to support high-capacity payloads and advanced propulsion systems to reduce upper stage fuel mass. Also, advanced bus technologies are needed for structures and autonomy. Critical technology areas include power generation with an increased power-mass ratio, energy storage with an increased specific energy-mass ratio, thermal control for high-power payloads, advanced propulsion for upper stages, advanced structures with reduced mass, and spacecraft autonomy to reduce operations cost.

Ground Segment. To provide cost-effective services, critical satellite ground segment elements that enable users to transparently access the highly integrated satellite and terrestrial systems of the future need to be developed. Advanced ground terminals that will significantly lower user costs, provide a 100-times increase in communications capacity, be dynamically interoperable with different satellites, and permit efficient interconnection with terrestrial networks are a targeted goal. Critical technology areas include standards and protocols, ultrasmall Earth terminals, optical gateways, advanced VSAT's, and phased arrays.

Advanced technology development with significant performance improvement, sizable reductions in mass and power consumption, and compatibility with commercial frequencies and formats is required now to enable global wideband interactive communications in 2005 and beyond.

NASA's Space Operations and Communications Technology Program

In 1995, the Space Operations Management Office (SOMO) was created to be the Agencywide provider for communications and space operations services. SOMO is faced with the challenge of meeting the strategic mission needs of the NASA Enterprises, while reducing the space operations costs. SOMO has instituted the Space Operations and Communications Technology program (SOCTP) to play a key role in the office's strategy to meet this challenge. The SOCTP will supply new capabilities that are required for SOMO to meet its strategic objectives. In addition, and possibly most significant, the SOCTP has an Agencywide responsibility to define NASA's program for future communications and space operations technology development. The SOCTP is a part of the HEDS Enterprise technology program because space operations is a key function of HEDS. The SOCTP consists of five elements: strategic planning, commercial satellite communications and operations, deep space communications and operations, Government-unique near Earth orbit communications and operations, with subelements of unmanned missions and manned missions, and terrestrial data distribution. The SOCTP Commercial Satellite Communications program leverages off of the growing, multibillion dollar commercial satellite communications industry. Key components of this program are:

- Strategic planning
- Technology development
- Validations and demonstrations
- Insertion/implementation planning

The SOCTP Commercial Satellite Communications Program Plan addresses, in detail, each of these four components. The following is a brief summary of each of the components.

Component 1: Strategic Planning. The strategic planning process starts with future visions of both the world and NASA at least 20 years ahead. A global commercial satellite communications network is conceived to serve the envisioned world, and space missions satisfying the NASA vision are examined. A commercial satellite communications architecture consisting of numerous satellite constellations, interoperable among themselves, and terrestrial networks is conceptually planned. From this architecture comes the identification of the technologies needed to enable both the future commercial services and NASA's use of them.

Component 2: Technology Development. Because it is envisioned that NASA's needs may drive the performance levels of future commercial satellite communications systems, it is imperative that NASA's technology program enable the development of commercial satellites that exceed performance levels matched to the evolutionary growth of commercial needs. In so doing, NASA will have a role in assisting the U.S. commercial satellite communications industry to maintain a leadership position in the world market. In addition, NASA may be the initial and only, for some period of time, customer in space, thereby creating the need for unique capabilities such as high-performance cross-links between NASA and commercial satellites or a commercial gateway ground stations. The technology program will be coordinated with those of other Government agencies and the Department of Defense in particular to take advantage of preexisting technologies and concurrent technology development programs.

Component 3: Validations and Demonstrations. A continuing impediment to industry in incorporating new technologies into space systems is the perceived risk associated with using new and unproven components and methods. The SOCTP will support technology demonstrations and validations of new communications systems and components, and it will sponsor applications experiments to test new or improved services. The technical verification of new systems and services helps mitigate the financial risk of the space communications industry.

Component 4: Insertion/Implementation Planning. To ensure that commercial space assets are used by NASA as early and as cost effectively as possible, extensive plans must be developed that take into consideration a transition period during which both Government and commercial services coexist, the timely enabling of new NASA satellites and space platforms (such as the ISS) to communicate with commercial systems, and the availability of reliable commercial assets when needed by NASA.

NASA conducts space operations with the goal of continually improving cost-effectiveness through a consolidated and/or integrated infrastructure. This infrastructure provides standard services and products to customer missions with the same ease, reliability, and economy as acquiring services and products from a public utility. The services and products consist of data services (such as data acquisition and data communication), mission services (such as data processing and mission control and navigation), and appropriate science information services. The standardized and interoperable NASA space operations system is essentially transparent to the customer, and the customer can acquire reliable service with minimal knowledge about the details of the system. The approach to achieving these goals is the implementation of an operational system that utilizes new technologies and adapts to match the needs of future customer missions.

The technology program is an integral part of NASA's strategy to move toward using commercial services to cost-effectively meet the Strategic Enterprises' space operations needs. This program will be used to stimulate competition in potential markets, to demonstrate the feasibility of using commercial services for Government needs, to validate the compatibility of Government and commercial assets, and to establish a convergent path for both NASA's and the commercial satellite communications industry's technology development.

Relationship of SOCTP's Commercial Satellite Communications Program and Strategic Technology Areas

The SOCTP is the top-level, overarching plan that addresses all of the customers' space operations and communications technology needs. The Commercial Satellite Communications element and the applicable subelements of the Strategic Technology Areas make up the majority of the SOCTP. Not all of the customers' space operations technology needs can be met by these efforts; therefore, additional elements of the SOCTP are required. The SOCTP team members will participate in the program strategy and implementation plan activities for each of the applicable Strategic Technology Areas and will incorporate those long-term plans into the SOCTP technology roadmaps and plans. The implementation of the SOCTP plan will consist of SOMO-funded activities, technology development, and demonstrations sponsored by other NASA programs and partnerships with industry, academia, and other Government agencies.

5.3 Commercial Remote Sensing

The commercial remote-sensing industry is a rapidly growing global industry with both aeronautical and space-based components. This industry—largely a “decision systems” industry—serves a broad spectrum of the economy (see Table 5.3–1). Commercial remote-sensing industry activities range from planning and developing new remote-sensing systems to applying remote-sensing information to customers’ real-world problems.

TABLE 5.3–1. KEY COMMERCIAL REMOTE-SENSING INDUSTRY MARKET SECTORS

<i>Market Sectors</i>	<i>Applications</i>
Commodities	Agriculture and forestry: chemical treatments and harvest forecasts
Urban Development	Land-use policy and zoning, flood control, emergency route planning, real estate development, and sales
Transportation	Roads, airports, and marine systems: planning, siting, and routing
Energy	Pipeline routing and monitoring, minerals exploration, and offshore platform management
Information	Mapping, news, and emergency management
Education	Geographical information
Environmental Management	Wetlands monitoring and regulatory compliance
Defense	Surveillance and mission planning
Science	Geology, geography, climatology, and biology

From its infancy in 1985 the commercial remote-sensing market grew to \$1 billion in 1993 and doubled to \$2 billion in 1996. The development of new technologies will spur growth to \$10 billion to \$20 billion by 2005 (see Figure 5.3–1). *The commercial remote-sensing industry is characterized by a set of global parameters that drive the commercial market—the need for real-time, near-real-time, and seasonal-time-span data of verifiable accuracy sufficient to support immediate decisions in commercial sector economics.* Market sectors and particular applications become viable when the needed type and accuracy of data are sufficiently available in a sufficiently timely fashion (see Figure 5.3–2).

The private-sector commercial remote-sensing industry and NASA’s Earth Science Enterprise are complementary to one another. Technologies and data from Earth Science Enterprise programs provide fuel for the growth of the commercial remote-sensing industry, which, as has always been the case, is the source of products and services to support that Enterprise’s Discovery and Scientific initiatives. As commercial markets have developed, the data and technology requirements of these markets increasingly have intersected with those of the Earth Science Enterprise (see Figure 5.3–3). Increasingly, technologies, services, and products—particularly data products—primarily developed for the commercial markets coincidentally meet Earth Science Enterprise requirements as well.

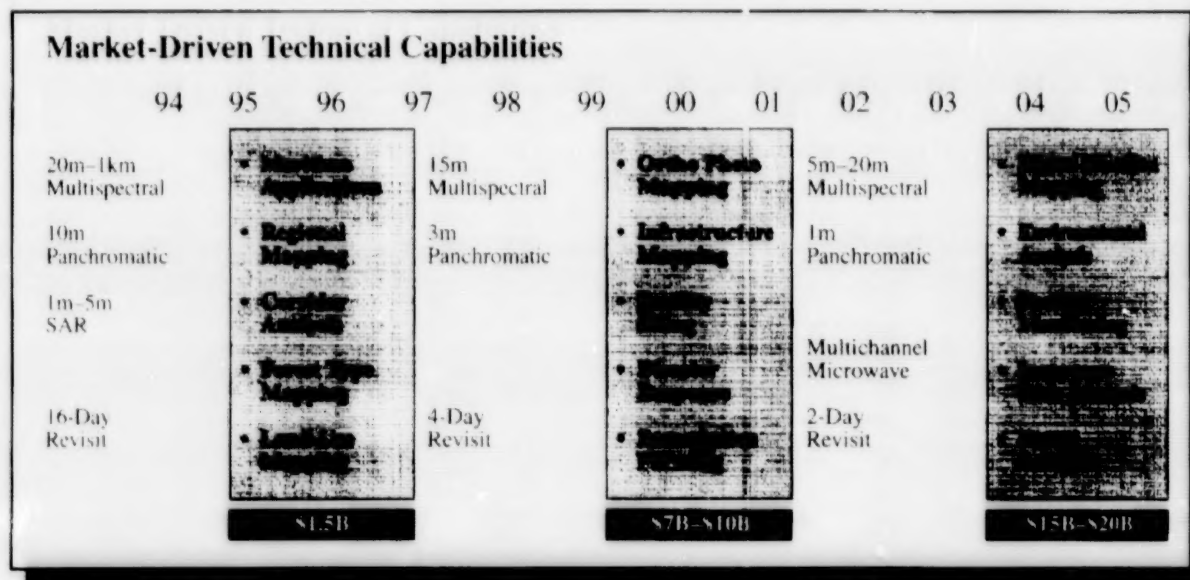


FIGURE 5.3-1. COMMERCIAL REMOTE-SENSING INDUSTRY MARKET AND TECHNOLOGY GROWTH

Commercial Remote Sensing Program Office

The Commercial Remote Sensing Program Office is chartered to foster U.S. commercial leadership in the global commercial remote-sensing market and to foster commercial sources of data and technology to meet the needs of NASA's Discovery and Scientific initiatives. In performing its mission, the Commercial Remote Sensing Program Office acts as a gateway between these two entities. In one direction, it manages the infusion of Government-developed technology into the commercial sector and pilot commercial applications of science mission data, and in the other direction, it manages the validation of commercial remote-sensing technologies and the flow of commercial data into NASA Earth science endeavors.

Strategic guidance for commercial remote-sensing industry technology is provided to industry through the NASA Commercial Remote Sensing Program Technology Plan. This plan provides roadmaps to guide industry, academia, and Government laboratory technology programs. In developing the plan, the Commercial Remote Sensing Program Office works with industry to characterize commercial technology needs and, similarly within NASA, to characterize scientific mission technology needs. It then formulates and implements projects in partnership with industry, academia, and Government laboratories to provide the needed technologies.

The Commercial Remote Sensing Program Office and the Earth Science Systems Program Office are two technology implementation organizations within the Earth Science Enterprise. The Earth Science Systems Program Office articulates technology requirements of NASA's Earth Science Enterprise programs while the Commercial Remote Sensing Program Office articulates those of the commercial remote-sensing industry and of scientific applications. Technology development initiatives are issued by the Earth Science Technology Office. The Commercial Remote Sensing Program Office supports Earth Science Enterprise mission requirements through commercial data purchases, which are enabled through technology infusions and verification and validation services provided by the Commercial Remote Sensing program to the commercial remote-sensing industry.

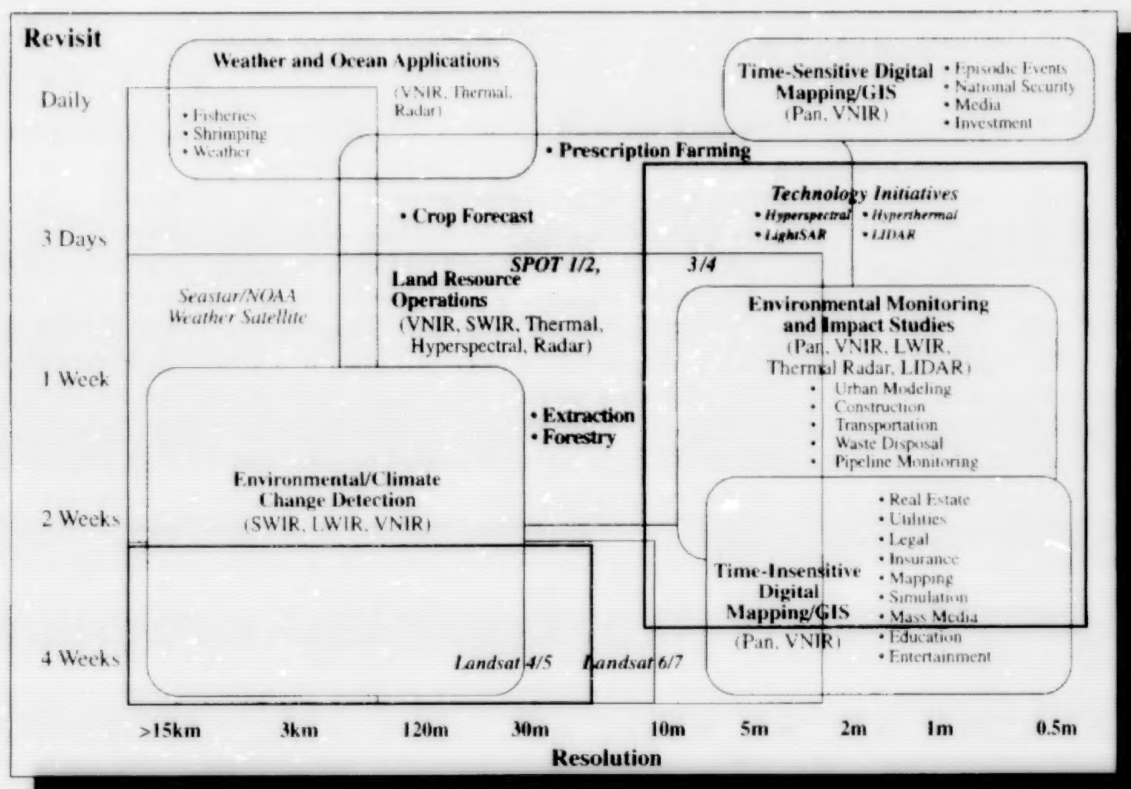


FIGURE 5.3-2. COMMERCIAL REMOTE-SENSING INDUSTRY MARKET SECTOR ANALYSIS

Commercial Remote Sensing Program Technology Plan

The Commercial Remote Sensing Program Technology Plan defines processes used by the Commercial Remote Sensing Program Office to implement the bidirectional technology gateway function for commercial remote-sensing industry systems keyed to both airborne and spaceborne remote-sensing platforms. The plan maintains a roadmap of industry-required technologies and defines the Commercial Systems Validation Laboratory, which enables the technology interchange by managing the validation of commercial remote-sensing technologies. The goals of the plan are to:

- Help foster U.S. leadership in the global commercial remote-sensing economy
- Facilitate the use of commercial data sets in Earth Science Enterprise scientific discovery/scientific theory and modeling
- Facilitate the use of Earth Science Enterprise scientific data and technology in commercial applications

Removing technological barriers is essential to promoting and maintaining U.S. leadership in the commercial remote-sensing industry and, as such, is a core function of the Commercial Remote Sensing Program Office. Commercial remote-sensing industry technology needs are varied; they include:

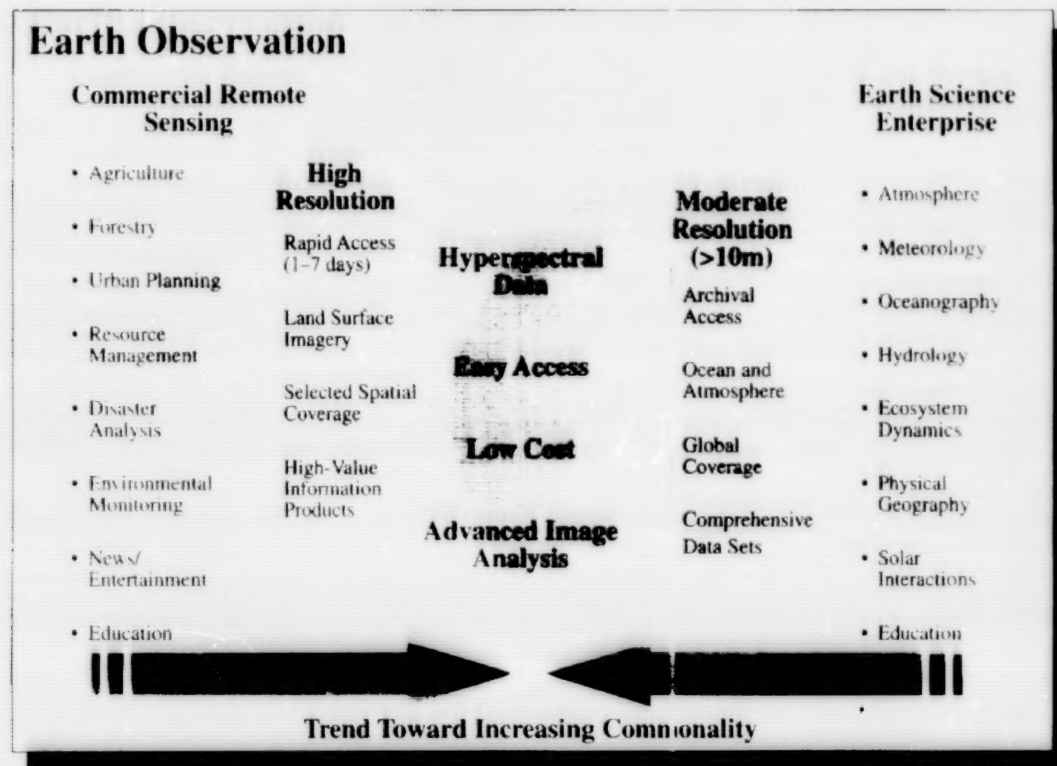


FIGURE 5.3-3. INTERSECTION OF SCIENCE AND COMMERCIAL TECHNOLOGY REQUIREMENTS.

- Mission and/or product simulation and analysis tools
- Low-cost, long-mission airborne platforms
- Low-cost, long-life space platforms
- Cost-effective and verifiable sensor systems
- Rapid data archive and distribution systems
- Algorithms for translating remote-sensing data into engineering and commercial applications
- Prototype applications for validating market potentials

The Commercial Systems Validation Laboratory

The Commercial Remote Sensing Program Technology Plan is implemented via the Commercial Systems Validation Laboratory. This laboratory is a geographically distributed ensemble of Government, industry, and university facilities. It has four major components by which the Commercial Remote Sensing program conducts test programs to validate the applicability of Government program technologies to industry needs and to validate industry technology and remote-sensing data sets to provide commercial sources to NASA.

Virtual Product Lab. The Virtual Product Lab is a network of computer simulation tools for demonstrating the viability of a commercial applications product or, vice versa, a science measurement data product. It provides various analyses, design trades, and data product simulations

supporting the remote-sensing system and data product design process. The Virtual Product Lab supports the technology program through mission system simulations to identify performance shortfalls that require new technology and the provision of a virtual environment for testing new processing algorithms and systems.

Commercial Instrumentation Validation Lab. This is a network of laboratories, centered at the Stennis Space Center in Mississippi, whose purpose is to characterize and validate the performance of commercial remote-sensing instruments. Here, established sensors undergoing the infusion of new technology are tested to measure performance improvement and to provide data to establish traceability between enhanced-system and previous-generation sensor performance.

In-flight Verification and Validation Network. This nationwide network of flyover sites (both engineered and natural) has been fully characterized for the sites' remote-sensing attributes to support in-flight test and verification of sensor performance and cross-validation between sensor systems. For technology, the In-flight Verification and Validation Network has a dual thrust: testing and validating new sensors for data set continuity and developing new system verification technologies. Figure 5.3-4 depicts the target of the Stennis-based flyover sites.



FIGURE 5.3-4. VERIFICATION AND VALIDATION TARGET AT THE STENNIS SPACE CENTER

In Situ Data Product Validation. This is the commercial remote-sensing program for data processing and information extraction methods. The in situ data product validation has ground-based field and laboratory operations as well as aerial vehicle, Space Shuttle, ISS, and commercial space mission operations.

Fostering U.S. Leadership in the Global Remote Sensing Economy

The Commercial Remote Sensing Program Technology Plan fosters U.S. leadership in the global commercial remote-sensing industry by characterizing and cataloging critical technologies required by the commercial industry to sustain growth, thus focusing efforts for technology development and infusion. The Commercial Systems Validation Laboratory contributes to this effort by providing systems and methods for evaluating and validating data, technologies, and systems.

In addition to the benefits to industry derived from the commercial data buys and from application development, as mentioned below, the Commercial Systems Validation Laboratory, through the services it provides, affords other benefits contributing to the leadership of the industry:

- The tools provided by the Virtual Product Lab provide industry with the means to simulate proposed data products, perform economic and system trades, simulate remote-sensing missions, and obtain information on remote-sensing resources.
- The In-flight Verification and Validation Network and the Commercial Instrumentation Validation Lab act as part of the infrastructure by which NASA provides resources to support industry. By means of these resources data providers can get independent evaluation, verification, and validation of their systems and data. In addition, the industry benefits in that the operations put in place for the In-flight Verification and Validation Network and the Commercial Instrumentation Validation Lab will help define standard methods and practices for accomplishing verification and validation.
- The Commercial Remote Sensing program has a long history of involvement in developing commercial applications of remote-sensing data. This involvement continues under in situ data product validation. As new data sources develop (such as high-spatial resolution, hyperspectral imagers, SAR, and LIDAR), in situ data product validation is actively involved in developing and validating the tools and applications that will make these technologies profitable for the commercial industry.

Use of Commercial Data Sets for Earth Science Enterprise Science. In keeping with NASA's "make-buy" policy, the Earth Science Enterprise has initiated a program to purchase commercial data for use by the Enterprise's science efforts. The Commercial Systems Validation Laboratory facilitates this data buy process through the use of the Commercial Instrumentation Validation Lab and the In-flight Verification and Validation Network for evaluation and validation of data to be purchased. The Commercial Instrumentation Validation Lab contributes by bench-verification of the performance of instruments used to collect the data, while the In-flight Verification and Validation Network contributes by providing in-flight verification of instrument performance. These contributions certify the quality of the data purchased by the Government.

Use of Earth Science Enterprise Scientific Data in Commercial Applications. The in situ data product validation is one of the means by which NASA scientific data are made useful to the commercial industry. Through the development of applications by which science data may be applied to solve real-world problems, the Commercial Remote Sensing program leverages the investment in science missions to the development of the commercial industry.

Commercial Remote Sensing Program Technology Roadmap. Figure 5.3-5 illustrate trends in the commercial remote-sensing industry's technology readiness, corresponding market evaluation, and relative shifts from Government spending to private investment. For example, it is expected that the currently dominant 10-meter Panchromatic imaging technology will advance to 1-meter Panchromatic capability in the 1999 timeframe and become the dominant Panchromatic technology by 2005 as the corresponding markets mature. The Commercial Remote Sensing program devises its programs to facilitate those trends; its technology roadmap defines the technology priorities necessitated by those trends. Table 5.3-2 provides a list of the more important of these technologies required over the next 15 years.

State and Direction of the Commercial Remote-Sensing Industry. The commercial remote-sensing industry is entering a period of rapid expansion. A number of commercial entities are ready to launch privately owned remote-sensing satellites to collect Earth imagery for sale to a wide array of markets—an unprecedented state of affairs. The data to be provided by these commercial providers and by foreign government and U.S. Government sources promise to increase data supply vastly and decrease the cost of data, thus creating the necessary conditions for rapid expansion in remote-sensing applications, products, and services. Along with this growth, the already wide range of remote-sensing data markets and applications is expected to grow as data costs decline. NASA can expect its missions to benefit significantly from this growth.

Role of NASA's Commercial Remote Sensing Program in Enabling the Industry. NASA has and will continue to play an active role in fostering U.S. leadership in the global remote-sensing industry, ensuring that the industry achieves self-sustainability in the short term and maintains pre-eminence in the long term. Through its Commercial Remote Sensing program, NASA has implemented a number of innovative programs that are complementary to the Commercial Remote Sensing Program Technology Plan and that are tailored and targeted to nurture the industry. Some of these programs are:

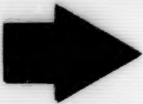

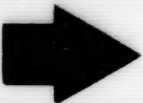
	<i>Current (1998)</i>	<i>Future Trends</i>	<i>2005</i>
Data Source Technology Readiness	<ul style="list-style-type: none"> • 6m-1km Multispectral (4m in 1999) • 4m Panchromatic (1m in 1999) • 11-Day Revisit (4-5 days in 1999) • 1-Month Data Delivery (2-3 days in 1999) 		<ul style="list-style-type: none"> • 5-20m Hyper-spectral • 2-5m SAR • 0.5m Panchromatic (upon review by NOAA) • 1-Day Revisit • <24-hour Data Delivery • Real-Time Data Fusion
Markets	<ul style="list-style-type: none"> • Regional Mapping • Agricultural Land Maps • Land Use/Land Cover • Corridor Analysis • Forest Mapping ~\$1.5 Billion 		<ul style="list-style-type: none"> • Digital Elevation Mapping • Media Events/Entertainment • Real-Time Weather • All-Weather Land-Cover Mapping (1m) • Prescription Farming • Environmental Monitoring • Vegetation Stress • Engineering/Site Analysis ~\$10-15 Billion
Agency Operating Procedure	<ul style="list-style-type: none"> • Government Funded, Owned, Operated • Some Private Data Distributions • Private Commercial 		<ul style="list-style-type: none"> • Private-Sector/Government Joint Ventures—New Millennium, ESSP, LightSAR, Earth Science Enterprise Phase II • Private-Sector Supplied Services: Data, Processing, Distribution

FIGURE 5.3-5. TRENDS

TABLE 5.3-2. CRITICAL TECHNOLOGY ROADMAP

Space-based	Air-based	1998-2002	2003-2007	2008-2012
X	X	Hyperspectral imagers	High-resolution hyperspectral imagers	
X	X	SAR and LIDAR topography	Thermal imagers	
X	X	High-spatial resolution topographical imagers		
X	X	SWIR, MWIR, and LWIR sensors		
X	X	Low-cost, long-life cryogenics		
X	X	Validation and verification (V&V) systems	V&V systems	V&V systems
X		Unpiloted airborne vehicles (UAV)	Long-mission UAV's	Low-cost UAV's
X		Small spacecraft	Microspacecraft	
X		Inflatable/deflatable structures		
X		MIMO guidance and navigation controllers	Intelligent guidance and navigation controllers	
X		100 MIP flight computers	1 GIP flight computer	
X	X	Application-specific information extraction tools		
X	X	Data compression	Real-time data fusion	
X	X	Soil moisture detection		
X	X	Chemical species detection		
X	X	Integrated synthesis environments		
X	X	Multidim visualization systems		
X	X	Regional data centers		
X	X	Data archiving and distribution		
		Digital Earth		

- *Earth Observations Commercial Applications Program (EOCAP)*—This program forms joint ventures between NASA and commercial firms to develop new products and technologies beneficial to NASA, the commercial partner, and the industry as a whole.
- *Affiliated Research Center Program*—Through this program, private-sector companies may be trained and informed on the techniques, technologies, and benefits of remote sensing. The program is offered at the Stennis Space Center and at several affiliated universities.
- *Earth Science Enterprise Data Buy*—This is the first of many efforts to purchase a significant quantity of commercial data to supplement or act as alternatives to planned Earth Observing System (EOS) data acquisition missions.
- *Mississippi Space Commerce Initiative*—This pilot program with the State of Mississippi is dedicated to the development and growth of the commercial remote-sensing industry in the United States. The initiative includes research to pilot new technologies and products, commercial development to aid companies in market access, and education and training to expand the workforce to meet the needs of the industry.

In the long term, NASA's Commercial Remote Sensing program will continue its efforts to foster U.S. industry leadership and will pioneer new approaches. Some of the principles guiding this strategy are:

- Coinvestment in high-risk or expensive research and development technologies by NASA and the commercial sector
- Investment by NASA where gaps exist in enabling infrastructure or technologies
- Availability of NASA's technology and scientific assets and expertise to industry

Continuation of intelligent NASA involvement in the industry will ensure industry growth, U.S. leadership, and the availability of technology, products, and services to meet NASA's evolving needs.

5.4 Space Processing

This industry sector is defined by a diverse and expanding group of entities that share a common goal of exploiting the unique attributes of space (primarily microgravity and ultravacuum) to produce products and services with commercial value here on Earth. For several decades, scientific investigations in the space environment have suggested that there may be a broad spectrum of commercial applications for the physical and biological phenomena that occur in Earth orbit. Unfortunately, U.S. companies exploring these applications have been limited by the relatively infrequent and short-duration flight opportunities offered by the Space Shuttle or sounding rocket flights.

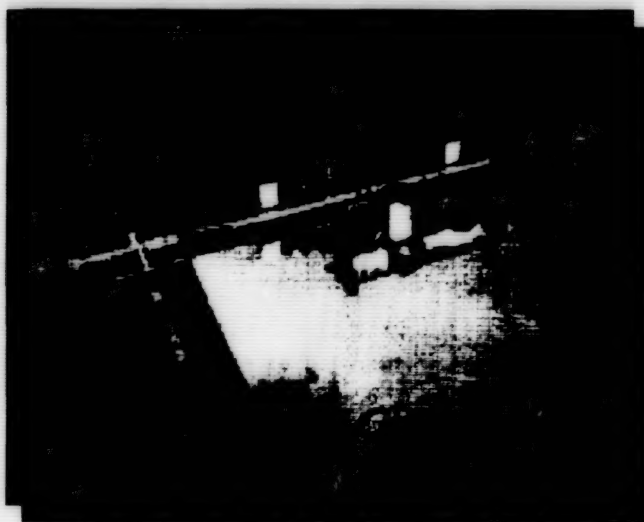


FIGURE 5.4-1. THE INTERNATIONAL SPACE STATION

The ISS (Figure 5.4-1) is about to change that situation. In addition to an orbiting research laboratory, it will provide a unique platform for industrial research and development. More than a decade ago, when NASA began plans for long-duration microgravity capabilities aboard an orbiting space station, the Agency also undertook an effort to stimulate this sector and to address the infrastructure and technology needs associated with commercial applications. As part of this effort, a number of Commercial Space Centers (CSC) were established at universities or nonprofit institutions in specific applications areas to encourage private-sector involvement and investment in these promising applications. A list of the CSC's

and their associated areas is included in Appendix A. Other CSC's will emerge as research and imagination suggest additional products and services.

A key objective of the CSC's is to establish jointly funded efforts with appropriate commercial, academic, and/or Government partners to explore the potential of specific applications up to and including NASA-sponsored flight studies aboard the Space Shuttle or other vehicles. The CSC's and NASA provide expertise to conduct space research, to build and operate space research hardware, and to ensure that technical interfaces and safety requirements are appropriately met.

Proprietary interests are safeguarded consistent with Federal legislation. In addition to the CSC's, several of the NASA Field Centers with relevant in-house expertise have established cooperative agreements with one or more companies to pursue specific applications.

Potential space processing application areas include biomedical, pharmaceutical, bioprocessing, biotechnologies, agricultural, environmental, semiconductor and optoelectronic materials, manufacturing analysis and properties, and combustion properties. The term *space processing* is often associated with manufacturing in space, but more frequently the real product from space is knowledge. In some cases, the knowledge product may be an improved understanding of the failure mechanisms in sintered alloys; in other cases, the knowledge may be very precise measurements of the thermophysical properties of new high-strength materials. If fully successful, any of these areas could lead to a significant space enterprise.

Sector Applications

Life and Biotechnology Applications. In microgravity conditions, biological systems and materials can function without the effects of fluid shears forces caused by buoyant convection. Consequently, fragile structures, such as three-dimensional tissue cultures, can form successfully, whereas in normal gravity they could not. Novel biological films and membranes can be formed of higher quality and greater uniformity. Applications include research for biomaterials processing, biomedical models, closed agricultural systems, and biomolecular electronics. Studies can be conducted at the cellular and subcellular level, including genetic processes, cell growth, and differentiation. Ultimately, the evolution of new materials may enable artificial body parts, such as joints, skin, lenses, valves, and membranes.

BioServe Space Technologies has projects under way in three diverse life and biotechnology areas. The biomedical and pharmaceutical project area explores new and improved pharmaceutical and nutraceutical products, and it develops new perspectives on a variety of physiological processes. The bioprocessing and biotechnology project area develops commercial products and services such as crystallization of biomaterials, manipulation of biological materials (for example, collagen, viral capsids, and "biocybernetic" proteins), separation technologies, and fermentation processes. The agricultural and environmental project area investigates the effect of microgravity on growing plants and plant systems. The emphasis is on finding commercial terrestrial applications of "lessons learned" in space to create new and improved food crops and forest products and to increase the yields of scarce, high-value pharmaceuticals derived from plants.

The Center for Macromolecular Crystallography is focused on developing technologies required for commercial application of protein crystallography, including forefront approaches for protein crystal growth in space. The center's objectives are to evolve new technologies for routine crystallization of proteins in space that do not produce high-quality crystals on Earth, to develop large-scale microgravity protein crystallization methods for processing protein pharmaceutical products and incorporate these into the design of a commercial protein crystallization facility, to continue the development of hardware systems and manufacturing processes, and to communicate knowledge to enable the structure determination of proteins and novel drug designs.

Materials Processing Applications. For materials processing, the two most significant attributes of space are its quiescence (absence of accelerations and vibrations) and the ultravacuum of space.

Without gravity, sedimentation and other separations events are suppressed, allowing for greater control of the organization and the processing of composite materials structures and increasing the significance of thermodynamic, heat, and mass-transfer phenomena at work in the formation of advanced materials. The ultrahigh vacuum of space is several folds cleaner than a vacuum created on the ground. Consequently, very pure and fine materials processes are enabled, such as the growth of very thin films.

The Center for Advanced Microgravity Materials Processing uses attributes of low-Earth orbit to develop novel technologies for sensors, films, ferroelectrics, diffusion studies, environmental cleanup, structural determination, and quantum dots. Crystal growth studies are conducted in solutions (proteins and zeolites), by vapor growth (mercury cadmium telluride), and by melt growth (gallium arsenide, mercury zinc telluride, and cadmium zinc telluride). The Center for Commercial Applications of Combustion in Space conducts varied activities using the unique behaviors of combustion processes in space. Diverse investigations into combustion phenomenon are under way for powders, catalytic processes, ash, water mists, glass, arrays, zeolites, diamond drills, and porous materials. The Space Vacuum Epitaxy Center conducts research with the Wake Shield Facility. The thin-film materials technology could lead to such applications as faster electronic components.

Automation and Robotics Applications. While much of the space processing industry creates products from the unique attributes of space, sectors of the industry are focused on the challenges of using the space environment. For space research and processes to be most effective, people must be assisted in detecting difficult-to-observe phenomena and in being "present" to conduct the experiment or industrial process. For success, technologies and systems must be created and used to enable remote researchers to visually, tactically, and by other means observe the dynamics of their materials and processes. Technologies that allow this include automation and robotics, advanced imaging technologies and other sensing technologies, and advanced human-machine interfaces.

In the area of automation and robotics, the Center for Microgravity Automation Technology specializes in the research, development, and transfer of advanced sensing, image processing, and automation-related technologies. These efforts are focused on increasing the effectiveness and productivity of microgravity and terrestrial laboratory research activities, especially through the use of telepresence. Technology areas currently under way include imaging microscopy, advanced image processing techniques, sample manipulation (robotics), and improved human interface technology. The Wisconsin Center for Space Automation and Robotics conducts applied research and technology development for the creation of transgenic plant materials to provide a more complete understanding of the biosynthesis of plant constituents having agricultural, industrial, and medical applications. The center is also involved in the commercialization of technologies and systems for automated plant-growing facilities, including advanced environmental control systems for space and Earth, and in the pursuit of using the technologies for the commercialization of related products useful in a range of other applications.

Technology Needs

Certainly, reducing the cost of access to space is a major factor in improving the economic viability of commercial space endeavors. However, another important key to nurturing and expanding

this sector is increasing the utility of space-based activities while decreasing their difficulty and cost. A series of workshops and working groups with industry, academia, and government have identified technologies associated with challenges to profoundly increase the effectiveness and reduce the cost of space-based industrial research and development. These technology challenges are listed in Table 5.4-1.

TABLE 5.4-1. SPACE PROCESSING TECHNOLOGY CHALLENGES

Technology Challenges	
The unique and harsh environment for habitation	
Remoteness from colleagues, family, and support systems	
Confined spaces and disturbances	
Logistics associated with transportation to and from space	
Scarcity of materials and personnel resources	
Implementation of sophisticated research and processes	

These combined challenges have a profound impact on the interaction between humans and machines, on collaboration among widely separated personnel, and on interactions and support with remote equipment. Operational time availability and real-time access become critical assets with the expense of orbital operations and with the demand for attentive support to vulnerable personnel and material assets. Advanced technologies that can provide expert human and equipment support systems on a constant basis are crucial. Intelligent systems and equipment that are capable of performing functions traditionally accomplished by humans are also critical.

While these challenges at first glance seem exotic and ambitious, a second look is warranted. These challenges of a harsh environment, difficult activities, and imaginative investigations and productive ventures have characterized all of humankind's pursuits since the beginning of our time on Earth. We are simply expanding our reach from Earth to space, because our reach and grasp, both physical and mental, are unprecedented and unforeseen. And as we learn to expand our reach into space, we expand the reach of most of humanity on Earth, to meet their aspirations for health, adventure, and happiness.

Technologies to Overcome a Unique and Harsh Environment. The same attributes of the space environment that make it exceptional for space processing also make it harsh to both humans and equipment. Materials and living organisms are strongly effected by the vacuum and radiation characteristics of space. Both radiation and strong vacuum cause accelerated aging of materials. Electronics are vulnerable to material damage and to electronic event upsets, which can alter or interrupt communications, data management, and systems control. Much of the effect of the vacuum environment can be avoided by enclosing personnel and equipment inside space platforms. Radiation, however, is not as readily mitigated. It is important to monitor radiation exposure and to design electronic and other systems to be impervious to radiation effects. One strategy is to reduce the reliance on film and magnetic media by using digital imaging and real-time downlinks of data. Some technologies required to mitigate the harsh environment of space include, but are not limited to:

- Radiation dosimeters, cosmic radiation-resistant radiography techniques and media (such as electronic), radiation-hardened electronics, radiation-resistant data media, and viewing windows
- Reduced-gravity physiology and low-gravity therapeutic crew countermeasures
- Vacuum-resistant coatings materials and processes

Technologies to Overcome Confined and Remote Workspaces. Research and manufacturing facilities on Earth are easily accessible to a spectrum of personnel, resources, equipment, and services. Earth's biosphere obviates the need for expensive life support and equipment support systems. Inexpensive transportation affects the scale and efficiency of our manufacturing and utility designs. The situation in space is dramatically different; habitable structures are at a premium and are confined and remote. Consequently, research and manufacturing space is highly limited and is remote from supporting organizations, supplies, and services. Yet, similar to research and manufacturing on Earth, we are concerned with occupational health and safety, the reduction or elimination of waste streams of gaseous emissions, rubbish, and the minimization of power requirements, sometimes to a more extreme degree. Technologies that can allow and improve the working environment in space include, but are not limited to:

- Noise reduction: quiet components and sound suppression
- Light management: stray light capture/blockage techniques, true color illumination, and light intensity control
- Breathable atmosphere: emissions control (vapors, particulates, and liquids) and emissions detection (O_2 , carbon dioxide, water, CH_4 , methanol, and so on)
- Comfortable atmosphere: humidity detection and control and heat rejection techniques (e.g. isothermal techniques)
- Electromagnetic interference control techniques
- Biological contamination: microbial detection and microbial decontamination/disinfection
- Vibration isolation systems
- Telepresence: telescience and augmented reality microscope

Technologies to Overcome Small and Disturbed Workspaces. Microgravity research and manufacturing has gone to space to access vacuum and reduced gravity. Much of the research is on phenomena that occur on a very small scale and are highly sensitive to acceleration disturbances. It is challenging to work in a manner in which the human's presence may detract from the research or manufacturing objectives. There is a need for technologies that allow for experimentation or manufacturing without the effects of human presence or that overcome human limitations in perception or manipulation. For example, technologies are needed to allow for combustion and protein crystal growth experimentation in miniature, while confining hazards for humans and shielding the experimentation from vibration disturbances or contamination by the crew and the space flight vehicle. In addition, the phenomena of study cannot be perceived without magnification or telescience to reveal the "science-in-a-box" to the investigators (see Figure 5.4-2). These technologies include, but are not limited to:

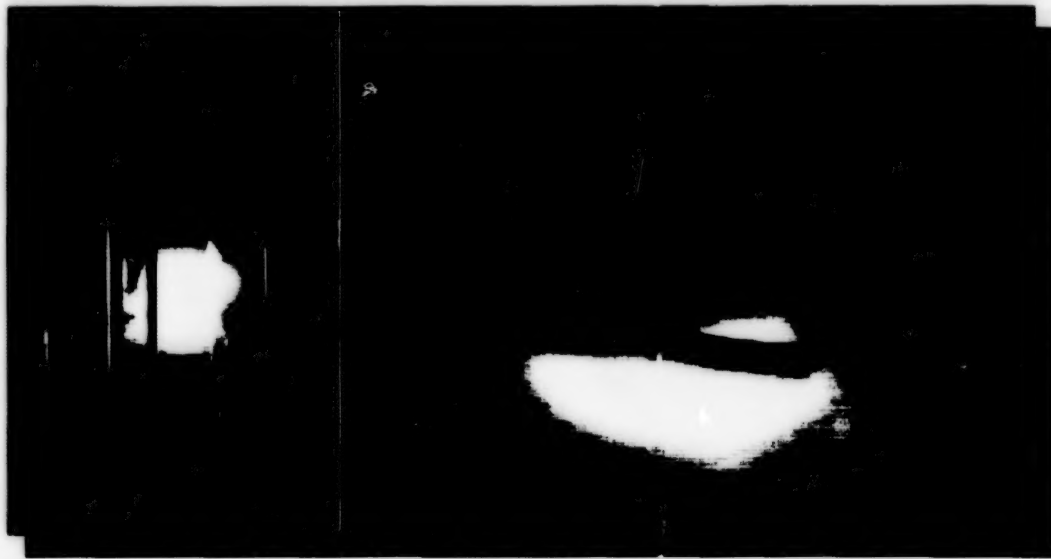


FIGURE 5.4-2. SCIENCE-IN-A-BOX (BOTH COMBUSTION SCIENCE AND PROTEIN CRYSTAL GROWTH ARE STUDIED IN MINIATURE, REQUIRING DELICATE AND REMOTE HANDLING AND CONFINEMENT.)

- Vibration isolation techniques and nonvibration transmitting umbilicals
- Advanced observation and sensing: miniaturized video systems, automated video systems, and miniaturized electronic
- Telescience: wireless communications, wireless (nonvibrating) data acquisition, and miniaturized robotic experiment manipulators

Technologies to Mitigate Transportation Demand and Access. The cost of access to space is a barrier to many commercial space processing ventures. In addition, the support logistics (size, shape, mass, power, and so on) associated with both the transportation system and the space platform are extremely difficult. Consequently, it is a priority in designing research and manufacturing hardware to strive to minimize transportation demands or to create flexibility in operations and resupply to allow reconfigurations to mitigate transportation limitations and bottlenecks. Strategies include the reduction or elimination of resupply, the elimination of requirements for transporting samples for analysis, the elimination of paper documentation, and so forth. Unpowered refrigeration or incubation hardware is needed. Technologies that can reduce the demand and create flexibility in transportation requirements include, but are not limited to:

- Resupply reductions: consumables replacements (filters and spares)
- Reagents: recycling systems for reagents, filter-free air/water purification, and filtration
- Power: batteries and waste energy recycling
- Data media: real-time imaging and image recognition versus film, real-time data downlink versus magnetic media, and compact digital data media
- Onboard experimental analysis and reconfiguration: automated sample processing, reconfigurable samples and experiments, telescience, augmented reality payload operations, standardized lockers/racks (that is, mounting hardware), automated planning/just-in-time crew training, and crew personal digital assistants

- Smaller experiments: sample miniaturization, reconfigurable experiment apparatus, superlight thermal insulation, and electronics miniaturization
- Portable, unpowered refrigerators/incubators for transport/transfer

Technologies to Mitigate Scarcities. Because of shortages in transportation, available space platform access, and limited human resources and utilities, space processing is constantly mitigating profound scarcities. Design approaches must minimize the need for supplies, people, utilities, and spares because they are difficult and expensive to provide, they may not be immediately deliverable, and there is little physical space for their accommodation. These challenges are similar to those posed by transportation. Consequently, most technologies that mitigate transportation demand and expense also address scarcities. In addition to transportation, there exist operational challenges posed by scarcity. Technologies that can help mitigate scarcities include, but are not limited to:

- Strategies and techniques to minimize crew time and power: automated planning/just-in-time crew training and crew personal digital assistants
- Low-power electronics: nanotechnologies
- Augmented reality payload operations

Technologies to Implement Sophisticated Research and Processes. In one sense, space processing is associated with difficult and sensitive activities, so much so that the terrestrial environment precludes their existence. Also, many of these activities are pushing the envelope of what is scientifically or physically possible. There are many advanced areas of research and manufacturing that demand the state of the art and beyond, laboratory capabilities, and manufacturing capabilities. There are many systems that must be designed and developed. They require available space and manned system qualified hardware and software systems and components. They require seemingly exotic equipment for highly specific ventures. Some areas of research and manufacturing that are destined for space flight today include: fluids and combustion research and development, ultralow-temperature phenomenon, biotechnology, materials science (inorganic and organic, films, fibers, crystals, and so on), cell and tissue culture, animal and human physiological processes, plant physiological processes, astroculture, microencapsulation of pharmaceuticals, and many others. Many technologies are relevant to many investigations and ventures, so interchangeability and modularity are key enabling characteristics for the enabling technologies. Some of the technologies required to enable the sophisticated research and processes include, but are not limited to:

- Observation and sensing
 - Advanced chemical sensors
 - Nonintrusive/nonperturbing chemical, physical, biological, and physiological sensors and instruments
 - Advanced radiation sensing and monitoring systems
 - Advanced video/visual capabilities
 - Advanced acceleration sensing systems and monitoring
- Environmental control and conditioning: ultralow electromagnetic interference noise insulation, isothermal heat rejection techniques, high-thermal-performance cooling devices, and microfluidics

- Automation and robotics: robotics, automated sample processing, reconfigurable robotic systems, teleoperations (telemedicine and telescience), virtual reality interface improvements, monitoring and control, third space environment, immersion reality environment, support robots, radiation-hardened electronics, radiation-hardened computer and data storage devices, and high-speed networks
- Information/communications: demonstration of graphical programming for flight project, embedded web software technology, immersion reality environment, onboard Internet/networking services, automated planning/jist-in-time training and crew personal digital assistants, distributed wireless internal communications, continuous wireless communications for mission control voice loops (voice communications badge), autonomous satellites for monitoring (personal satellite assistant), and compact digital image interface
- Operations and mission support: telemedicine, telebiology, medical monitoring and intervention, standardized payload interfaces/packaging, virtual payload operations centers, teleoperations workstation, automated payload reconfiguration, data visualization via synthetic environment, and ISS "common" electrical power control unit and supporting technology



6.0 Space Science Technology Programs

6.1 Space Science Approach to Technology

Strategy

The development of new capabilities and innovative techniques is central to the Space Science Enterprise (SSE) strategy. Therefore, the approach to technology development is aimed at delivering technology products to meet the requirements derived as described in Section 3.1. In addition, SSE is responsible for administering a Crosscutting Technology Development Program that responds to those needs that are common to two or more Strategic Enterprises.

Policies

SSE has established the following policies to guide the technology development programs:

- Each SSE mission will contribute to the advancement of space flight technologies, science instrument technologies, or ground systems technologies to ensure that new technologies continue to become available for use on future missions (*OSS Integrated Technology Strategy, 1994*)
- SSE-sponsored technology developments must be relevant to SSE goals and missions. However, developments funded through the crosscutting program must be relevant to two or more Strategic Enterprises.
- Technical excellence—determined by periodic peer reviews (at both critical stages: selection and performance evaluation)—is the standard for technology efforts funded by SSE.
- The SSE technology program is based on broad participation from industry, universities, and Government to foster excellence through the contributions of the most qualified and innovative investigators and teams.

- Space flight missions will be approved for development only when their enabling technologies have been demonstrated to be ready.
- SSE strives to maintain an optimum balance of technology "push" (low TRL technology not yet selected for a mission) and technology "pull" (more mature technology being developed in response to needs derived from a future mission or missions). This policy recognizes the challenge of maintaining a continuous flow of technology products through increasing TRL as the cost of development grows by severalfold (frequently approaching an order of magnitude) from one TRL to the next.

6.2 Technology Program Structure

The SSE technology program, which has five components, is currently undergoing radical restructuring to implement the newly issued *NASA Procedures and Guidelines 7120.5A* and transfer several management functions to the Field Centers. The following describes a framework for the restructuring, rather than a completed program structure.

The ambitious space science program described in the SSE Strategic Plan requires a commitment to an aggressive and carefully planned program of technology research, development, and utilization, in which mission concepts and supporting technologies are developed in synergism. A critical aspect of planning is the context provided by companion programs inside and outside NASA. Inside NASA synergism is vigorously pursued with the technology programs of the Earth Science Enterprise (particularly in areas related to remote sensing) and the Aero-Space Technology Enterprise (particularly in the area of propulsion) and with the Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR) programs. Outside NASA, the most synergistic programs are with various organizations in the Department of Defense, the Department of Energy, the National Oceanic and Atmospheric Administration, and several Independent Research and Development programs in industry.

Five-Component Technology Program

Space Science Core Technology Program. This program develops mission-specific technologies for space science at early TRL's—typically less than or equal to 4. This program supports enabling technologies for the next generation of high-performance and cost-effective space science missions. An aggressive technology development approach is used that allows all major technological hurdles to be cleared prior to a science mission's development phase. Retiring technological risk early in the mission design cycle and emphasizing innovation to reach previously unattainable goals in mass reduction and performance are key to the success of many of the missions planned for the next century. Much of this program is funded through the crosscutting technology development appropriation, because often the commonality of needs among Enterprises is greater at early stages of technology readiness.

Focused Program. The Focused Program is dedicated to specific high-priority areas of the space science strategy. The projects in this program are generally designed to satisfy specific requirements and correspond to TRL's that are greater than or equal to 4 all the way to infusion into flight missions. Occasionally, they may include lower TRL's as a part of an integrated attack on critical problems with both short- and long-term impact (such as flight computers). They are driven by the

needs of SSE, but other Strategic Enterprises may also benefit from them. There are presently five Focused Technology Projects:

Mars Technology. This program develops critical technologies for the Mars Surveyor program. Mars Surveyor is currently undergoing a major replanning to accommodate in the assigned budget profile two missions in each of the 2001 and 2003 launch opportunities (including a possible major international contribution) leading to the Sample Return Mission planned for launch around 2005. Work to date indicates that the principal focus of this program will be ascent propulsion (conducted in collaboration with the Aero-Space Technology Enterprise), planetary surface mobility, sample acquisition and analysis, and energy storage.

Advanced Deep Space System Development. This program develops, integrates, and tests revolutionary technologies for solar system exploration. Emphasis is on microavionics, autonomy, computing technologies, and advanced power systems. Along with other technologies, these are integrated as an advanced engineering-model flight system to form the basis for the new generation of survivable, highly capable microspacecraft.

Astronomical Search for Origins Technology. This program develops critical technologies for studies of the early universe and of extrasolar planetary systems. Included are large lightweight deployable structures, precision metrology, optical delay lines, and other technologies for space-based interferometry. Also included are such technologies as inflatable structures and large lightweight optics that are required by many proposed missions and concepts.

Structures and Evolution of the Universe Technology. This program provides the technologies required for missions focused on understanding how the structure of our universe emerged from the Big Bang, how the universe is continuing to evolve, and what the fate of the universe will be. Examples of technology in this area include sensors, detectors, and other instruments especially for high-energy radiation and particles, as well as cryocoolers and other instrument support systems.

Sun-Earth Connection Technology. This program develops the technologies needed for missions focused on understanding long-term solar variability, and how solar processes affect Earth. Technologies supported in this area include thermal shielding, integrated fields and particle sensors, and a high-temperature solar array.

Flight Validation Program. The Flight Validation Program completes the technology development process by validating technologies in space. The cornerstone of this program is the New Millennium program. New Millennium missions are driven by needs for technology validation, but are also designed to return high-priority science data within cost and mission constraints. Additional flight validation platforms, including the ISS and STS, balloons, sounding rockets, and spacecraft or launch vehicle piggyback opportunities, may also be utilized as possible to validate technologies in the relevant space environment. Industry-Government partnerships are used to identify technology candidates, complete their development, and select them for flight. The New Millennium program is supported by both SSE and the Earth Science Enterprise.

Advanced Concepts Program. This program has two efforts directed to the far term (> 25 years). One is to elicit and develop far-reaching ideas—revolutionary, but plausible—into feasible

technological concepts that provide imaginative options for future space endeavors. These options may either (1) expand the envelope for strategic goals and objectives or (2) expand the toolkit of future mission capabilities. These options lead to longer range goals and to new fundamental technology research. The other effort is to create a vision and conceptual frontier for the advanced mission and technology communities. This involves (1) the development of new strategic and technological visions that would stem from anticipating unprecedented technological capabilities of the future and (2) the development of cutting-edge tools and techniques, such as out-of-the-box thinking for generating, infusing, and adopting advanced concepts.

Crosscutting Technology Development Program. As mentioned in Section 6.1, SSE also manages the Crosscutting Technology Development Program (CCTDP) to meet joint needs of two or more Strategic Enterprises, specially at low TRL. These efforts are pursued in the technology-push approach to respond to the Enterprises' strategic challenges for which specific technology needs have not yet been characterized. Many of the efforts in the Base R&T Program are funded by the CCTDP, which is NASA's primary source of low-TRL spacecraft technology. It supports all three of NASA's "space" Enterprises. The goal of the CCTDP is to develop cutting-edge, revolutionary technology that enables bold new missions to address Enterprise science and exploration goals. Emphasis is on basic research into physical principles, the formulation of applications concepts, and component-level performance evaluation. Where appropriate, these developments may extend all the way to subsystem-level development and test for nearer term missions, with joint development and funding from customer Enterprises. Examples include miniaturization, autonomy, innovative design methods, robotics, and quantum-sensing detectors. These crosscutting developments are the foundation for most new spacecraft, robotics, and information technologies eventually flown on NASA missions.

A synopsis of the SSE technology portfolio is shown in Figure 6.2-1.



FIGURE 6.2-1. THE SSE TECHNOLOGY PORTFOLIO

Mission Studies

Although not directly part of the technology portfolio, mission studies are intimately involved with technology development in two related ways. First, they guide technology development from the early conceptions (at low TRL), responsive to broad science challenges, to laboratory validation. The guidance is realized, as explained at the end of the "Space Science Technology Planning" subsection in Section 3.1, by testing the applicability of the technology in more and more realistic settings as the performance of the technology becomes better defined and more certain. Second, mission studies—at varying degrees of definition—help evaluate and compare the benefits of competing technology approaches accruing to appropriate sets of future missions. These estimates of benefits, together with estimates of development cost and development risk, are the basic factors for funding decisions.

6.3 Description of the Technology Program and Roadmaps

The technical content of the technology program may be best summarized by describing the plans or roadmaps for each of the 10 key capabilities defined earlier in Section 3. Table 6.3-1 provides the 10 roadmaps with milestone capabilities specified at 5, 10, and 25 years from now and compared with the present state of the art. The table also contains references to the Strategic Technology Areas as appropriate for SSE support (AM = Advanced Miniaturization, IS = Intelligent Systems, CS = Compact Sensors and Instruments, SH = Self-Sustaining Human Support, DS = Deep Space Systems, and SE = Intelligent Synthesis Environment).

6.4 Management of Space Science Technology

Management Principles

SSE's management of technology development is guided by two principles: (1) adherence to NASA's Strategic Management Handbook and the new Program Management Guideline (NPG 7120.5A) and (2) organization of the work according to technology "products." Technology products are end-points of technology development efforts. They are devices or capabilities that can be adopted by projects for engineering application.

Typically, missions stating technology needs describe these needs in terms of products and the product's needed performance characteristics. A general rule of thumb for defining a technology product is that it is the largest system or it fulfills the broadest function to which a single TRL can be assigned.

In the CCTDP, "products" are managed in connected sets called "thrusts." The connections that define a thrust are varied. Some thrusts collect products related to the class of mission they enable or enhance. Other thrusts cluster products around a grand challenge, such as very small autonomous spacecraft or constellations or formations of spacecraft. A few thrusts may focus attention on new space technology disciplines, such as astrobiology.

TABLE 6.3-1. KEY TECHNOLOGY CAPABILITY ROADMAPS:
PERFORMANCE, PRODUCTS, AND USING MISSIONS VERSUS TIME

Now	5 Years	10 Years	25 Years
Key Technology Capability			
Structures			
(IS, CS, SH)			
<ul style="list-style-type: none"> • Many low to moderate precision deployments already occurring • First flight test of microdynamics of deployable structures • 10^{-7}/degree Celsius Coefficient of Thermal Expansion of composite structures 	<ul style="list-style-type: none"> • Flight deployment of 2- to 4-meter diameter structures • Shape control to 25-micron root mean square • New Generation Space Telescope inflatable sunshield flight experiment • 5-percent structural damping lowest 20 modes • Enabling for Origins missions 	<ul style="list-style-type: none"> • Flight deployment of 8- to 10-meter diameter structures • Control structure to 25-micron root mean square • 10^{-8}-degree Celsius Coefficient of Thermal Expansion of composite structures • Enabling for Origins missions 	<ul style="list-style-type: none"> • Flight deployment of 20- to 25-meter diameter ultralight structures • Control shape to 1-micron root mean square error for 25-meter via ultralight structures • 10^{-9}-degree Celsius Coefficient of Thermal Expansion of composite structures • Enabling for Origins missions
Communications			
(AM, IS, DS)			
<ul style="list-style-type: none"> • Pathfinder: 10 kilobytes per second from Mars for high-resolution color imaging • 30-centimeter X-band spacecraft antenna • 70-meter ground antenna 	<ul style="list-style-type: none"> • 1 megabyte per second from Mars for high-definition television • 30-centimeter optical spacecraft telescope • 10-meter ground receiving telescope • Lightweight, low-power, robust communications electronics • Lightweight antenna materials • Enhancing technology for all missions 	<ul style="list-style-type: none"> • 100 megabytes per second from Mars approaching IMAX quality • 50-centimeter optical spacecraft telescope • 10-meter ground receiving telescope • Lightweight, low-power, robust communications electronics • Lightweight antenna materials • Enhancing technology for all missions 	<ul style="list-style-type: none"> • 10 gigabytes per second from Mars for Mars trunk line integrating orbiter, lander, and rover data • 100-centimeter optical spacecraft telescope • 10-meter ground receiving telescope • Lightweight, low-power, robust communications electronics • Lightweight antenna materials • Enhancing technology for all missions
Design Tools			
Operations			
(IS, SH, DS, SE)			
<ul style="list-style-type: none"> • Skunk works • Colocated teams • Hardware/software breadboard and test antenna 	<ul style="list-style-type: none"> • Collaborative engineering • Tele-engineering • Model-based design • Benefits all missions 	<ul style="list-style-type: none"> • Three-dimensional real-time model-based design • Design visualization • Distributed engineering • Benefits all missions 	<ul style="list-style-type: none"> • Spacecraft design synthesis • Quick turnaround design • Formal verifications • Benefits all missions

<i>Now</i>	<i>5 Years</i>	<i>10 Years</i>	<i>25 Years</i>
Key Technology Capability			
Lightweight Optics (AM, IS, CS, DS, SE)			
<ul style="list-style-type: none"> • Hubble Space Telescope mirror at 250 kilograms per square meter • Space Infrared Telescope Facility prototype at 25 kilograms per squared meter 	<ul style="list-style-type: none"> • Segmented optical systems of 2- to 4-meter diameter • Precision optical control to 150 nanometers • Large lightweight mirrors of 2-meter diameter at 15 kilograms per squared meter • Enabling for Origins missions 	<ul style="list-style-type: none"> • Segmented optical systems of 8- to 10-meter diameter • Precision optical control to 50 nanometers • Large lightweight mirrors of 4-meter diameter at 15 kilograms per squared meter • Enabling for Origins missions 	<ul style="list-style-type: none"> • Thin-film transmissive optics of greater than or equal to 25-meter aperture • Segmented optical systems of greater than or equal to 20-meter diameter • Inflatable reflective optics of greater than or equal to 25-meter aperture • Precision optical control to 30 nanometers • Large lightweight mirrors of 4-meter diameter at 1 kilogram per squared meter • Root mean square figure good enough for optical imaging • Enabling for Origins missions
Metrology (AM, IS, DS, SE)			
<ul style="list-style-type: none"> • Laboratory testbeds at 1 micron absolute and 250-picometer relative precision over 1-meter lengths 	<ul style="list-style-type: none"> • Image-based wavefront sensors for infrared telescopes • 50-picometer relative metrology over 10-meter lengths • Enabling for Origins missions 	<ul style="list-style-type: none"> • Image-based wavefront sensors for visible telescopes • 50-picometer relative metrology over 100-meter lengths • Enabling for Origins missions 	<ul style="list-style-type: none"> • 50-picometer relative metrology over tens of kilometer lengths • Enabling for Origins missions
Power (AM, IS, SH, DS)			
<ul style="list-style-type: none"> • 18-percent efficiency, 50-watt-per-kilogram solar cells • 50-watt-per kilogram Ni-H₂ batteries • 5 watts per kilogram at 855-watt radioisotope thermoelectric generators (RTG) • 32-kilogram PuO₂ RTG fuel for Cassini • Tolerant of Jupiter radiation belts • Beneficial for all missions 	<ul style="list-style-type: none"> • 25-percent efficiency, 100-watt-per-kilogram solar cells, all solar to 5 AU for Champollion; inflatable panels • 100-watt-per-kilogram Ni-H₂ batteries • 12 watts per kilogram at 150-watt RTG's • Less than 2-kilogram PuO₂ RTG fuel for X2000, Pluto, Europa • Less than 10-gram PuO₂ for Mars, Europa • Tolerant of Jupiter radiation belts, Mars poles • Beneficial for all missions 	<ul style="list-style-type: none"> • 30-percent efficiency, 150-watt-per-kilogram solar cells, possible all solar for outer planet flybys; inflatable panels • 150-watt-per-kilogram Ni-H₂ batteries • 15 watts per kilogram at 10-watt RTG's • Less than 200-gram PuO₂ RTG fuel for outer planet orbiters and probes • Less than 10-gram PuO₂ for Mars polar probes, Europa subsurface • Tolerant of Jupiter radiation belts, Mars poles • Beneficial for all missions 	<ul style="list-style-type: none"> • Greater than 30-percent efficiency, 200-watt-per-kilogram solar cells, possible all solar for outer planet orbiters; inflatable panels • Less than 200 watts per kilogram from advanced Li polymer batteries • 20 watts per kilogram at 10-watt RTG's • 100-gram PuO₂ RTG fuel or light reactor for approximately hundreds of AU, NEP • Tolerant of Jupiter radiation belts, Mars poles • Beneficial for all missions

Now	5 Years	10 Years	25 Years
Key Technology Capability			
In Situ Sampling (AM, IS, CS, SH, DS, SE)			
<ul style="list-style-type: none"> • Mobile science laboratories with approximately five integrated instruments for planets, comets, space physics • Organic compound detection • Subsurface penetrators with high-g-tolerant instruments (Mars 98/01/03 and Champollion) • Comet coma sample return (Stardust) 	<ul style="list-style-type: none"> • Minibiochemistry laboratories to detect amino acid chirality; wet chemistry laboratory; MEMS sensors on a chip • Minigeochronology sensor with miniature mass spec and laser-ablated samples • Comet nucleus and asteroid sample returns • Enabling for Mars program 	<ul style="list-style-type: none"> • Long-range airborne and surface integrated mobile science laboratories with up to 10 physical, chemical, and biological measurements at and below-planet, satellite, asteroid, comet surfaces • Rad-hard electronics and sensors working at temperatures found on Mars, Venus, Titan, comets, asteroids • Pristine rocks, soils from Mars, comets, asteroids • Smart instruments (with humans) for surveys • Enabling technology for Mars, Venus, Titan, small bodies 	<ul style="list-style-type: none"> • Long-lived mobile science laboratories capable of multidiscipline interactive measurements • Sophisticated data analysis, fusion, and information extraction • Multidimensional sensors on a chip using MEMS technology • Pristine samples of outer planets and their satellites • Smart autonomous instruments for surveys and samplers (without humans) • Enabling for landers on solar system bodies
Instruments (AM, IS, CS, SH, DS, SE)			
<ul style="list-style-type: none"> • 100-micron features for electromechanical systems • Integrated instrument suite with common electronics (Deep Space 1 and MICAS at 12 kilograms, 12 watts, \$8 million) 	<ul style="list-style-type: none"> • 25-micron features in electromechanical micro-instruments (e.g., hydrometer) • Optical and infrared space-based interferometry • Enabling for Origins and Structure & Evolution of the Universe (SEU) missions 	<ul style="list-style-type: none"> • 10-micron devices used in electro-mechanical-optical instruments such as a weather station • Higher resolution, wide-bandwidth imaging and spectroscopy, Synthetic Aperture Radar (SAR), and radar sounding • Inflatable structures and optics for science craft • Matched electronic and sensor operating temperature for integration • Enabling for Origins and SEU missions 	<ul style="list-style-type: none"> • Nanometer-scale optical, quantum, or biological devices • Integrated sensors from gamma ray to megawatt with automated analysis and event-driven response • Automated continuous surveys of solar system with less than 100-kilogram spacecraft and 10 watts per suite • Enabling for Origin and SEU missions
Spacecraft Systems and Intelligence (AM, IS, SH, DS, SE)			
<ul style="list-style-type: none"> • Single spacecraft at 180 kilogram • 0.5-micron feature size with 5-volt rad hard 	<ul style="list-style-type: none"> • Formations of spacecraft (virtual spacecraft) at 90 kilograms • 0.35-micron feature size with 3.3-volt rad hard 	<ul style="list-style-type: none"> • Precision constellations of 40-kilogram spacecraft over hundreds of kilometers, with centimeter precision 	<ul style="list-style-type: none"> • Massive three-dimensional swarms of 1- to 10-kilogram spacecraft (virtual presence throughout solar system)

<i>Now</i>	<i>5 Years</i>	<i>10 Years</i>	<i>25 Years</i>
Key Technology Capability			
Spacecraft Systems and Intelligence <i>(Continued)</i>			
<ul style="list-style-type: none"> • Card-based, backplane architecture • Subsystem boxes and cabling • 100-kilogram avionics • Preprogrammed sequences 	<ul style="list-style-type: none"> • Reconfigurable and programmable logic gates • Multichip modules and multifunctional modules for power, communications, data • Three-dimensional flex interconnects • 35-kilogram avionics subsystem • Semi-autonomous planning and operations • Benefits all missions 	<ul style="list-style-type: none"> • 0.18-micron feature size with 1-volt rad hard • Fault-tolerant, reconfigurable and programmable logic gates • Three-dimensional stacked chips and multichip module systems • Avionics systems on a chip • 10- to 15-kilogram avionics • Fully autonomous operations with decision making and fault tolerance • Benefits all missions 	<ul style="list-style-type: none"> • Less than 20-nanometer single electron quantum devices • Molecular nanotechnology • Biological computing • Bio-electronic-optical hybrid technology • Integrated, intelligent, multifunctional, reconfigurable, ultralow-power microsystems • Less than 1-kilogram integrated avionics • Thinking systems with onboard scientific and operational expertise • Benefits all missions
Mobility (AM, IS, CS, SH, DS, SE)			
<ul style="list-style-type: none"> • Delta V of 2.1 kilometers per second for Cassini • Tens of meters range for Sojourner with 11.5-kilogram mass • High-altitude, short-lived Venera balloons on Venus • Stereo high-definition television on Pathfinder for science analysis • Real-time public image dissemination 	<ul style="list-style-type: none"> • Delta V of 10 to 15 kilometers per second from multimission SEP • Solar sail of 20 grams per square meter • Tens of kilometers with 50-percent science payload for Mars rovers • 0.5-kilogram nanorovers for comets, asteroids, local Mars surface • Home broadcast of high-definition television space images • Automatic real-time space images via Internet • Stereo high-definition television for operations, sample arm, navigation • Lighter (to be determined) high-temperature atmospheric entry systems • Beneficial to Mars, outer planet missions 	<ul style="list-style-type: none"> • Delta V of 30 kilometers per second with advanced SEP • Delta V of 50 kilometers per second with 5-gram-per-square-meter solar sail • Enables multibody sample return • Megawatt EP to support piloted Mars missions • Mars mobile science laboratories with hundreds of kilometers range • Subsurface explorers to several kilometers depth on Mars, Europa • Scaleable mass from 0.1 to 100 kilograms • Aerobots circumnavigating Mars, Venus, Titan • Stereo IMAX-quality images for operations and science • Stereo high-definition television to homes • Lighter (to be determined) high-temperature atmospheric entry systems • Beneficial to Mars, outer planet missions 	<ul style="list-style-type: none"> • 100 kilometers per second SEP • 1-gram-per-square-meter solar sail • Delta V of 500 kilometers per second using antiproton-catalyzed microfission/fusion • Interstellar robotic missions and piloted exploration of solar system • Autonomous laboratories circumnavigating Mars and interacting with humans • Nanorover swarms with hundreds of kilometers range • Europa ocean exploration • 4X resolution of home digital video • IMAX-quality stereo panoramas in home without viewing aids • Real-time "virtual" roaming on planet and satellite surfaces • Lighter (to be determined) high-temperature atmospheric entry systems • Beneficial to Mars, outer planet missions

Crosscutting technology thrusts are equivalent to "projects," in the terminology of NPG 7120.5A. Not all the thrusts have been fully identified at this time, but it is expected that about a dozen of them will be defined by the beginning of FY 1999. Projects in the Focused Program are managed within the program they support (e.g., the Mars Surveyor program).

Management Organization

Technology management is a shared responsibility of NASA Headquarters and designated Field Center program management offices. The primary management structure at Headquarters consists of the assignment of the oversight of each program to a Program Executive (except that mission studies are divided between two Program Executives).

Special arrangements have been instituted for the management of the CCTDP, because SSE serves as a steward of this program for all three NASA "space" Enterprises. In this case, program management is divided approximately equally between a Formulator and an Implementor, with their functions assigned to Field Centers. In addition, the Jet Propulsion Laboratory has established a Technology Planning and Integration Office to perform overall systems analysis, trade studies, metrics analysis, and investment portfolio analysis primarily of SSE technology needs and products.

Program Management Approach

Formulation Phase. All programs conduct a formulation phase and update it annually. This phase sets overall program goals and needs, establishes program policies, conducts systems analyses and trade studies, develops roadmaps, and publishes an implementation plan. For the CCTDP, this formulation function is performed by a dedicated Formulator at the Goddard Space Flight Center. In this case, of course, the scope of goals, needs, policies, and analyses span the three NASA "space" Enterprises and support NASA's Strategic Technology Areas.

Approval Phase. In most cases, program approval is divided between Headquarters and Center program offices. Headquarters typically approves at the program or project/thrust level, and the Center program offices approve technology development product selection and implementation plans. Approval of the Crosscutting Program Implementation Plan is retained at NASA Headquarters. In addition, the final selection of products to be implemented in the broadly announced, peer-reviewed portion of the program is retained at Headquarters. Approval of product selection for the inhouse capability portion of the CCTDP is a duty of the CCTDP Implementor.

Implementation Phase. The implementation of all SSE technology programs is in conformance with approved implementation plans. Such implementation is managed (overseen) by the responsible Center program offices (the Implementor in the case of the CCTDP), and, of course, technology development is conducted by technologists selected from the entire U.S. technology community through the balanced application of the SSE technology policies cited in the "Policies" subsection of Section 6.1.

An important objective at the later TRL's (≥ 5) is to maximize the infusion of technology into missions or space qualification flights. This is accomplished, in part, by establishing a firm

commitment from (1) the NASA project manager to baseline emerging technology for the project, (2) the NASA Field Center technology provider to deliver a mature and tested technology product, and (3) the Headquarters customer office to establish a stable funding line in support of the infusion effort. Typically, at this TRL level (> 5), the funding will be shared between the technology development line and the project. A memorandum for the record, concurred with by all three parties, will be developed as part of the project documentation to formalize these agreements and to establish a baseline and milestones for future reviews of the technology maturation progress. These memoranda will be referred to as "Technology Commitment Agreements."

Assessment Phase. The assessment of all SSE technology programs is a responsibility of Headquarters. Such assessment relies on three primary methods:

- Continual Program Executive oversight, review, and monitoring of Center technology programs and recommendations and comments received about them from the wide variety of program stakeholders
- Regular review and evaluation of required programmatic metrics
- Periodic structured nonadvocate reviews at both the product level, chartered by program offices, and the program level, chartered by Headquarters, either at the Program Executive or Division level.

SSE is constantly sensitive to indications of the need for further assessment and review and institutes ad hoc assessments or reviews as indicated.

6.5 Impact of the Technology Program

SSE recognizes the importance of measuring the performance of the technology program to maximize its utility and to satisfy customers and funding sources. SSE also recognizes the difficulty of developing a set of metrics that cope with the following:

- Frequently imprecise relationship between use of technology and results
- Delay between technology infusion and outcome
- Difficulty of separating and attributing merit in synergistic efforts (for example, "spacecraft" implementation)
- Difficulty in assessing the benefits (for example, higher resolution images may help or even enable new discoveries, but in ways not directly quantifiable)

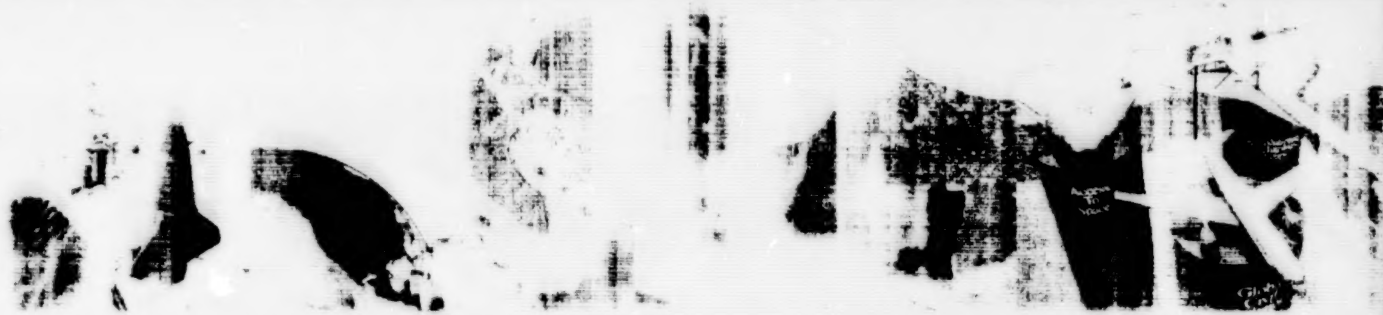
Thus the preliminary metrics concepts that are now being formulated will be adopted for FY 1999 and will be carefully evaluated with the assistance of external committees and modified as appropriate to achieve the goals of the technology program. Two categories of metrics are being studied: (1) customer satisfaction (both project managers and ultimate science users) and (2) performance benchmarks. The first is qualitative and will be based on structured independent interviews with the affected project managers. Within the second, we have identified three classes of measurement:

1. *Product Metrics* show whether the technology program meets the needs and requirements of the science programs. Examples are: number of technology products baselined at pro-

ject starts; number of mission starts that would not have been possible without a product originating from the program; and number of Technology Commitment Agreements.

2. *Mission Process Metrics* show whether the technology program contributes to improving the engineering and manufacturing systems we employ to implement our missions. Examples are: elapsed time from start of the space flight project to launch; mission cost (as estimated by the Project Design Centers with the use of old and new technology); and mission risk.
3. *Technology Process Metrics* show whether the technology program is improving the way it selects and implements the development of technology products. Examples are: elapsed time to progress from selected TRL's; number of technologies selected for flight without the burden of a space flight demonstration; number of new "products" invented; absence of "gaps" in the technology pipeline from TRL = 1 to TRL = 7; and number of extramural participants.

While no single metric is adequate, it is believed that a judicious selection of half a dozen among the above examples can provide good guidance to the technology program.



7.0 Earth Science Technology Programs

7.1 Enterprise Approach to Technology

Until recently, much of the technology development benefiting Earth Science Enterprise (ESE) missions was developed within the framework of individual missions. This approach ensured that the development activities were well focused on actual mission needs, but it placed an emphasis on short-term development and missed synergistic opportunities for leveraging activities ongoing within the broader technology community. This approach also lacked the ability to nurture breakthroughs that provide alternate, less expensive approaches to implement ongoing measurements or enable entirely new measurements.

The technology planning process initiated in 1997 consolidates the requirements of many potential missions and allows a synoptic perspective of the Enterprise's technology needs. During 1997, the Enterprise produced the first Capability and Needs Assessment. One outcome of this activity has been the identification of additional needs within the Enterprise's program. Notable in this area was the recognition of a gap between NASA's low TRL programs (such as the Crosscutting Technology Development Program and the SBIR program) and ESE space flight programs. The Enterprise has taken an important step to address this programmatic deficit by forming the Instrument Incubator Program (IIP).

Future solicitations that will address the ongoing measurement needs of the Enterprise will incorporate both technology development and science measurement scenarios. The future of the ESE science research depends on the integral implementation of both science and technology developments.

Figure 7.1-1 shows the strategic roadmap for the ESE's technology development program. This roadmap indicates the particular Enterprise programs and initiatives that will be deployed to meet the fundamental ESE strategic goals.

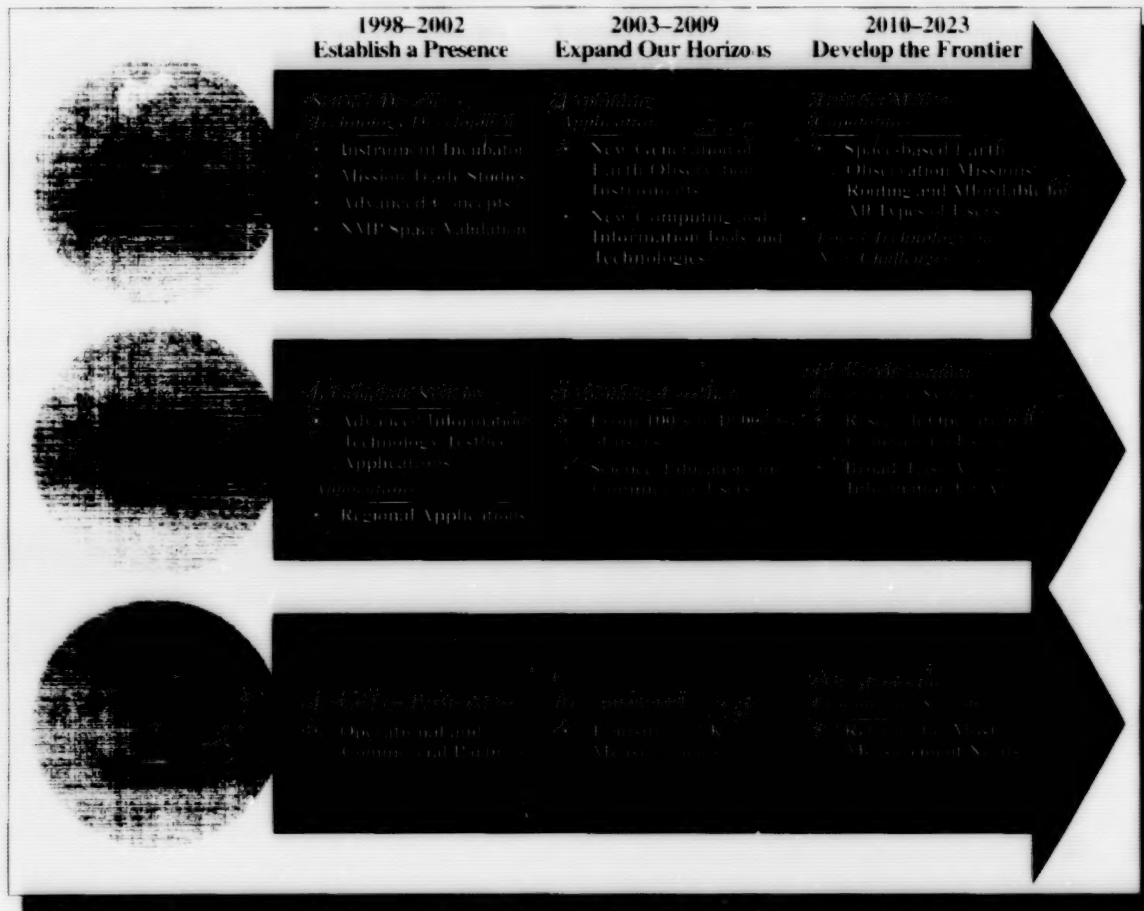


FIGURE 7.1-1. STRATEGIC TECHNOLOGY ROADMAP FOR THE EARTH SCIENCE ENTERPRISE

Near-Term Activities

In the near term (1998-2002), ESE will expand scientific knowledge by characterizing the Earth system. In support of this effort, the ESE technology development program will implement:

- Mission and system trade studies to evaluate and prioritize technology needs and opportunities beyond the first Earth Observing System (EOS) series missions
- The IIP to advance and mature instrument and measurement systems
- The Technology Acceleration Program (TAP) to advance critical component technologies
- The Technology Investment Program (TIP) to promote technology-push developments
- Advanced concepts studies (Advanced Concepts Program) to examine alternative system implementations and approaches to address unmet challenges
- The New Millennium program to space-validate revolutionary technologies

In the near term, the technology development program will support the dissemination of information about the Earth system by implementing:

- The High Performance Computing and Communications (HPCC) program to address Earth system modeling "grand challenges"
- An Advanced Information Technology Testbed to evaluate alternative system architectures

Also in this timeframe, the technology development program will support the productive use of Enterprise science and technology in the public and private sectors by implementing:

- Cooperative Technology Development Agreements with industry and operational agencies to ensure an early buy-in of a technical approach and facilitate the future infusion of technology
- Regional applications and validation technologies to facilitate the use of ESE information for public and private applications

Midterm Activities

In the midterm (2003–2009), ESE will expand our understanding of Earth system changes. In support of this effort, the ESE technology development program will:

- Demonstrate a new generation of small, highly capable active, passive, and in situ instrument and measurement systems derived from the IIP
- Develop the computing and information system technologies needed for predictive models to forecast and assess the state of the Earth system
- Develop adaptive, autonomous mission and systems operations technology to reduce long-term mission operations support and allow science investigator-driven, adaptive measurement implementations

In the midterm, the technology development program will support the dissemination of information about the Earth system by:

- Developing tools to expand the information system science and nonscience user base from hundreds to tens of thousands
- Developing an information architecture that effectively mixes private, Government, and international data sources and users

Also in this timeframe, the technology development program will support the productive use of Enterprise science and technology in the public and private sectors by:

- Implementing Cooperative System Development Agreements to begin the transition of key, long-term sustained measurements to industrial and operational partners
- Validating broad applications of Earth system information for regional and local governments, educational organizations, and commercial systems

Long-Term Activities

In the long term (2010–2023), ESE will expand scientific knowledge by forecasting and assessing the state of the Earth system. In support of this effort, the ESE technology development program will:

- Transfer mature instrument, measurement, and mission system technologies to operational and commercial partners, making the acquisition and use of new and existing space-based information more routine than today's airborne observations

- Demonstrate predictive modeling, data assimilation, and adaptive data acquisition systems that support and enable the forecasting of decadal changes and regional impacts
- Focus advanced technology efforts on new science challenges and directions

In the long term, the technology development program will support the dissemination of information about the Earth system by:

- Deploying an international global observing and information system with space-based and in situ components
- Demonstrating a collaborative synthetic environment to facilitate understanding and the remote use of models and results

Also in this timeframe, the technology development program will support the productive use of Enterprise science and technology in the public and private sectors by:

- Completing the transfer of all routine measurement systems to commercial and operational observing systems
- Demonstrating the linkage of operational and commercial systems into an integrated global observing system
- Transferring applications technology for the local and regional use of environmental data for economic decisionmaking

7.2 Organization and Structure of the Technology Program

ESE is initiating technology programs to address those specific needs that cannot be met through existing, cross-Enterprise programs. Current activities include:

- The IIP competitively selects instrument and measurement systems for development. The scope of the IIP ranges from concept studies to engineering models and aircraft or field demonstration. The IIP will not address individual, component-level developments, which are covered in the Technology Acceleration and Core Technology Programs. An essential role for the IIP will be to support continued development of instrument technologies too mature for the lower TRL programs but not sufficiently mature for space flight. The majority of program funding will be allocated to innovative, high-payoff instruments selected via a competitive process. Activities will be led by Principle Investigators and will allow for potential commercial applications and industry and non-NASA coinvestment.
- The Technology Acceleration Program is focused on accelerating developments by partnering with ongoing programs funded either external or internal to the ESE programs (such as the Office of Space Science's Crosscutting Technology Development Program) to bridge funding so as to speed up the maturation of technologies critical to Enterprise infusion needs (that is, technology items essential to meet decision dates or funding for special cases for time-critical experiments of opportunity with commercial, interagency, or international partners).

- The Technology Investment Program is focused on funding technologies for future instruments, spacecraft, and information systems that are crosscutting in nature but not specifically driven by ESE science requirements (that is, "technology-push" developments). Technology maturation times are expected to be from 5 to 10 years.
- The Advanced Concepts Program is focused on supporting technology concepts and applications, including analytical or experimental demonstration of the critical function (proof-of-concept), that if successfully developed would radically improve progress toward the Enterprise's goals.

In addition to Enterprise-unique technology programs, ESE expects significant synergy with ongoing Agency programs, such as:

- The joint Earth Science and Space Science Enterprises' New Millennium program
- The Space Science Enterprise's Core Technology Program
- The Aero-Space Technology Enterprise's SBIR and Environmental Research and Sensor Technology (ERAST) programs
- The Human Exploration and Development of Space (HEDS) Enterprise's SOMO programs
- The joint Aero-Space Technology, Space Science, and Earth Science Enterprises' High Performance Computing and Communications program
- The NASA Office of Equal Opportunity Programs' minority university research programs
- The NASA Office of Human Resources and Education's Experimental Program to Stimulate Competitive Research and Space Grant programs

The New Millennium program supports the space demonstration of revolutionary instrument, spacecraft, and ground system technologies requiring system-level space flight validation prior to use in a science mission. The program identifies potential breakthrough component technologies and system capabilities through joint industry, academia, and Government integrated product development teams. Selection criteria for flight are (1) the revolutionary nature of the breakthrough, (2) the potential impact on the science return per cost for high-priority science investigations, and (3) the need for and value of operational space flight validation. Products developed within the IIP may become candidates for New Millennium program flights if they require space flight validation.

The NASA and external technology development programs that ESE will leverage can provide relevant advances in component- and system-level technologies and validation opportunities. The Enterprise will negotiate coinvestment as appropriate to enhance the leveraging potential. The Enterprise's strategy is to establish strong links to these programs to maximize mutual benefit. Internally funded activities within the commercial sector are more difficult to penetrate because of proprietary considerations. Open competitions for Enterprise-supported technology programs will be used whenever possible to attract the best ideas and capabilities from the broad technology community, including industry.

Where no effective leverage can be identified for high-priority technology development needs identified through the integrated planning process, the Enterprise will support these activities directly. Figure 7.2-1 illustrates the relationships among the various programs.

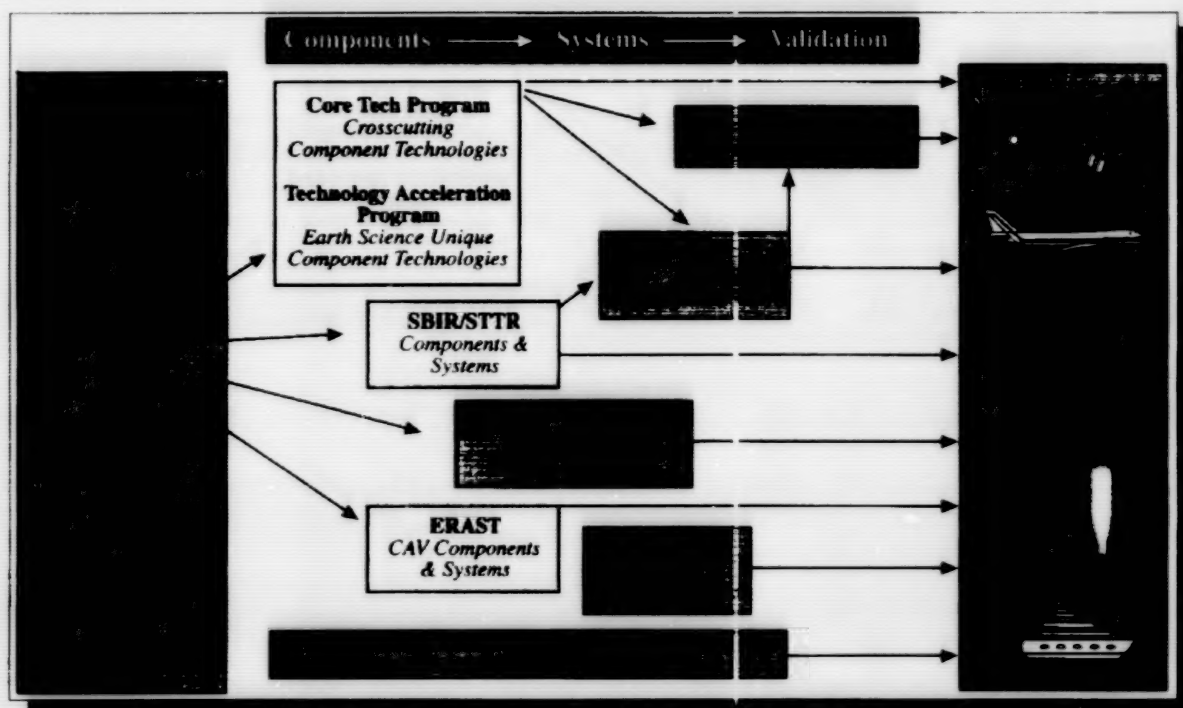


FIGURE 7.2-1. TECHNOLOGY DEVELOPMENT PROGRAMS SUPPORTING EARTH SCIENCE MISSIONS

7.3 Major Elements of the Technology Program With Roadmaps and Significant Milestones

Some specific technology developments that correspond to the three major areas of investments—advanced instrument and measurement technologies; cutting-edge technologies, processes, techniques, and engineering; and an advanced end-to-end mission information system—are as follows:

1. Advanced instrument and measurement technologies:

- Radar:

- Low mass and power radio frequency electronics
- Bistatic global positioning system (GPS) navigation
- Deployable millimeter-wave antennas (approximately 2 meters)
- High-power space-qualified 94-gigahertz amplifier tubes

- Lidar:

- Small, rugged stable laser sources with high energy (greater than 1 joule per pulse at 10-hertz double pulses), tunability (greater than 80 picometers across H₂O absorption line in 940-nanometer region), wavelength locked to water line, narrow linewidth (< 0.25 picometer), and high spectral purity (> 99.5 percent)
- Three-joule laser oscillator and amplifier with conversion efficiency greater than 10 percent at approximately 1 micrometer, 20 hertz
- Reliable, high-efficiency doubling and tripling crystals

- Radiometry:
 - Single L-band and multiple L- and S-band, dual polarization imaging radiometers
 - Lightweight, mechanically steerable microwave antenna
 - Compact, low-power electronics
 - Higher operating temperature visible and infrared detector arrays
 - Efficient on-orbit coolers and radiators
 - Smart sensors/algorithms for feature detection
- 2. Cutting-edge technologies, processes, techniques, and engineering:
 - Precise interspacecraft metrology
 - Autonomous stationkeeping
 - Atomic oxygen-resistant materials effective in orbits as low as 250 kilometers
 - Advanced batteries that provide 60 watt-hours per kilogram for 30,000 cycles
 - High-efficiency (> 20 percent), lightweight (> 50 watts per kilogram) solar arrays
- 3. Advanced end-to-end mission information system:
 - Radiation-hardened processors and data storage devices
 - Smart data compression algorithms
 - Fault tolerance and graceful degradation built into hardware and software
 - High-speed radio frequency or optical data transmission systems compatible with existing protocols
 - Advanced data display and visualization systems

Table 7.3-1 illustrates the mapping of the technology areas to the technology programs.

TABLE 7.3-1. MAPPING OF MEASUREMENT CONCEPTS TO TECHNOLOGY PROGRAMS

<i>Programs</i>	<i>IIP</i>	<i>TAP</i>	<i>TIP</i>	<i>Adv. Concepts</i>	<i>New Millen.</i>	<i>Core Tech.</i>	<i>SBIR/STTR</i>	<i>HPCC</i>	<i>SOMO</i>	<i>ERAST</i>
Technology Areas										
Advanced Radiometry	X	X			X					
Radar Methods	X				X					
Advanced Lidar	X	X			X					
Ground-Based, in Situ Methods				X			X			
Advanced GPS Methods	X	X			X					
Advanced Navigation	X	X	X			X				X
Batteries and Solar Arrays			X			X				X
Material Properties			X			X				X
Advanced Software			X	X			X	X		
Advanced Data Transmission				X			X		X	
Advanced Data Visualization							X	X		

7.4 The Value/Impact/Benefit of the Technology Goals in Accomplishing the Future Vision of the Enterprise—The Payoff for the Investment in Technology

New technology will play a major role in shaping ESE's program of the future. NASA's technology programs support the development of new instruments, measurement techniques, spacecraft, and ground and information systems. They also support the full range of Earth science missions from low- to geosynchronous Earth orbit altitude, as well as complementary measurements from airborne and ground platforms. In addition to advancements in flight hardware and software, engineering design and analysis tools, manufacturing processes, and test and simulation methods are also important targets for innovation and receive an appropriate level of inclusion.

NASA's technology programs support a balanced technology investment portfolio and leverage synergistic activities with other technology programs to achieve maximum benefit to ESE. This investment balances near-term, mid-term, and long-term investments and focuses on critical, high-payoff Agency and ESE needs and opportunities. All activities, in the near, mid, and far terms, have measurable near-term milestones and deliverables.

7.5 How Enterprise Technology Content Is Determined

Whenever possible, all ESE technology development programs shall use open competitions to encompass the best ideas and capabilities from the broad technology community. For those essential cutting-edge technologies in which NASA has a long-term strategic interest to meet long-term ESE scientific goals, the Enterprise shall establish sustained investments at selected NASA Centers. Senior ESE management shall examine the strategic directions established by Earth science, the technology needs and opportunities, the potential benefit of the investment, and an assessment outside capabilities. The ESE technology planning process proceeds through the steps described in the Figure 7.5-1.

The results of these steps are documented in the following four regularly updated documents:

- The ESE Capability Needs Assessment Matrix defines the systems-level capability requirements derived from the science measurement priorities.
- Technology options and trade studies translate the systems capabilities into technology performance requirements and compare the relative merits of competing approaches.
- The Integrated Technology Development Plan provides prioritized technology goals and the plan for achieving them through NASA and external technology development programs.
- The Technology Infusion Plan identifies the planned missions that will incorporate the technology advances as they are achieved.

The organizational structure of the ESE technology program incorporates elements of the entire Enterprise. Figure 7.5-2 introduces the component offices and their relationships.

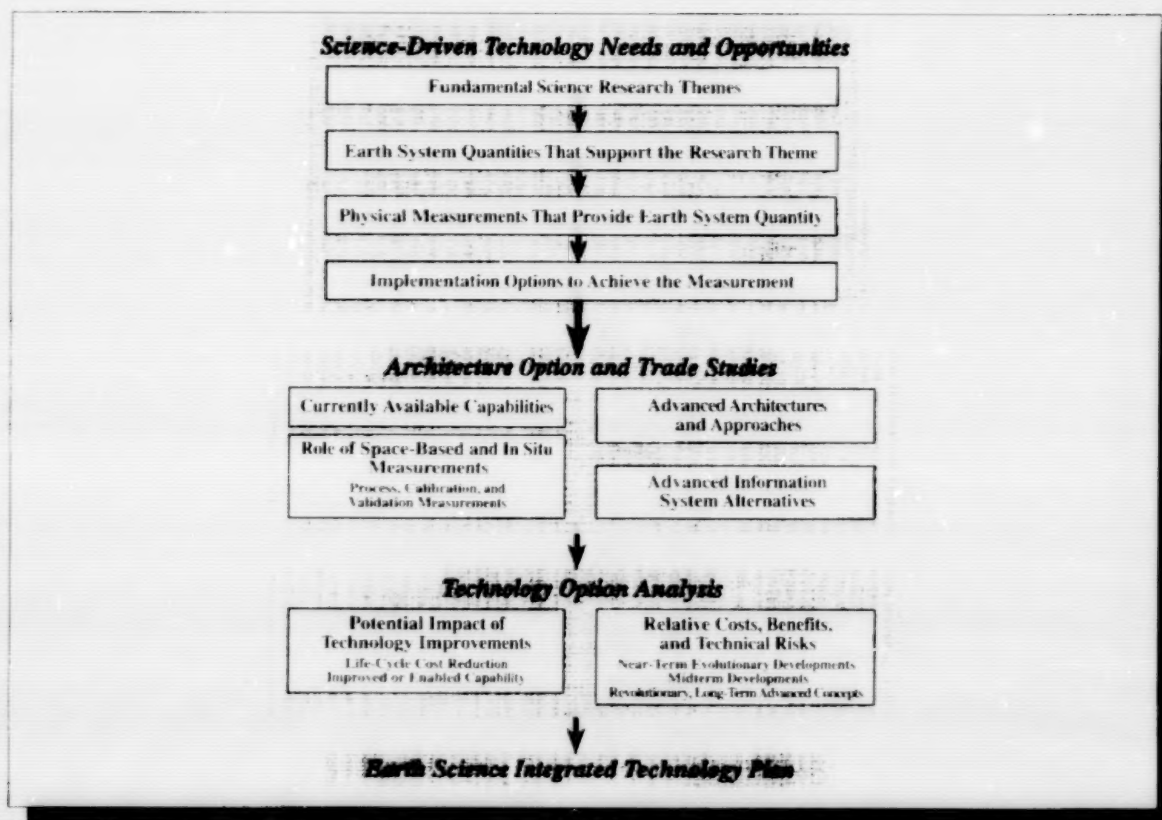


FIGURE 7.5-1. AN INTEGRATED TECHNOLOGY PLAN FOR THE EARTH SCIENCE ENTERPRISE

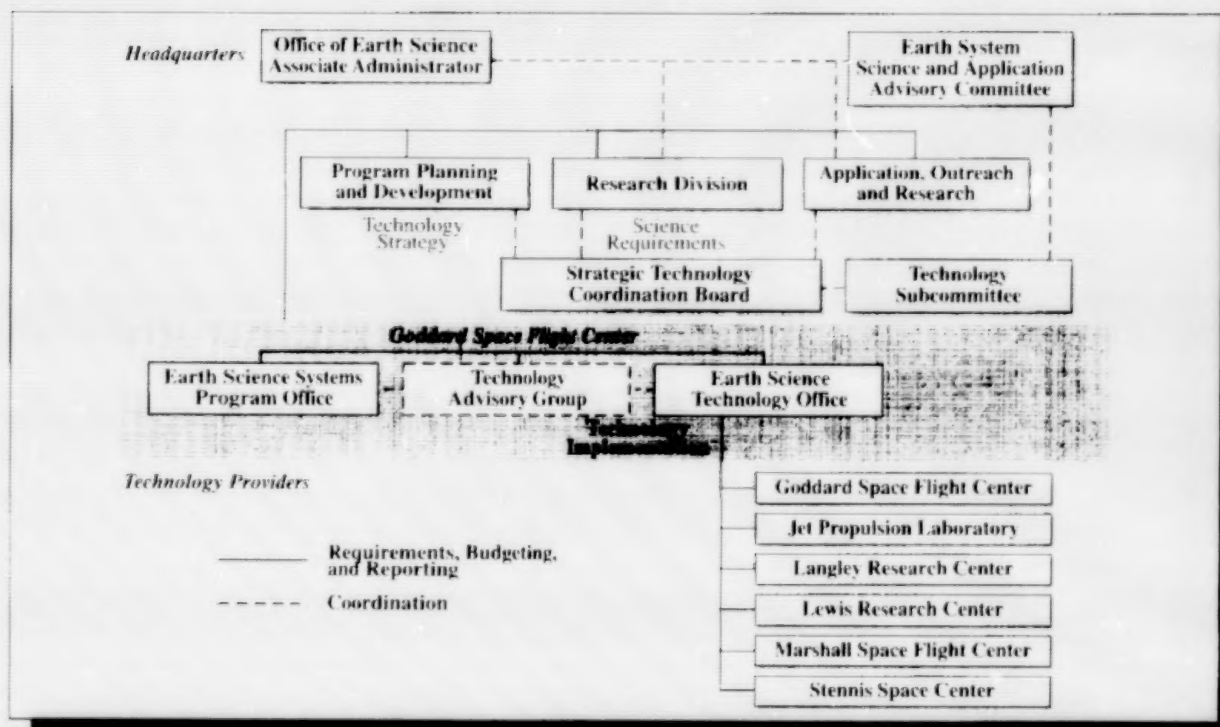


FIGURE 7.5-2. EARTH SCIENCE TECHNOLOGY PROGRAM PARTICIPATING ORGANIZATIONS



8.0 Human Exploration and Development of Space Technology Programs

8.1 Enterprise Approach to Technology

The Human Exploration and Development of Space (HEDS) Enterprise approach to technology involves a mixture of reliance on other organizations and a dedicated development of critical technologies. For example, HEDS has a wide variety of technology research and development activities under way, addressing diverse technologies at all stages of maturation for application in the near, mid, and far terms. These investments include technology maturation and infusion into the Space Shuttle program, technology developments associated with the International Space Station (ISS), such as the X-38 program, and longer term technology efforts (such as in the area of advanced human support technology).

In FY 1998, because of overall funding constraints resulting from the ISS program requirements, a substantial fraction of HEDS research and development investments associated with longer term strategic goals (specifically the HEDS Advanced Projects program) was for the most part terminated. Although the Enterprise plans to continue to make near- and midterm technology investments, as well as selected far-term research and development efforts, in the immediate future, HEDS plans only to study options for the longer term human exploration goals in support of the National Space Policy. These efforts will be accomplished through a small cadre of civil service employees across the NASA Centers, along with international and industry partners. The studies will examine a number of potential mission objectives and scenarios to identify and evaluate technologies that might provide significant improvements in areas such as cost reduction, supportability, and operations. It is expected that these technologies will include the areas of

propulsion, power, life support, communications, navigation, and others and that they will involve exploration of the Moon, Mars, and asteroids. As ISS schedule milestones are accomplished, the HEDS Enterprise will pursue the advanced technology initiatives needed for human exploration.

The HEDS Enterprise plans to be proactive in soliciting and assessing advanced concepts from all sources. Also, while for the most part HEDS will rely on research and development from several Enterprises to accomplish its broad technology goals, nevertheless the systems-level technology developments needed by HEDS to accomplish its strategic objectives (for example, at TRL 5 and above) will be unique to the Enterprise. These developments will be conducted by HEDS in partnership with the Office of Aero-Space Technology in some areas of space transportation technology.

At the level of technology research and early validation (for example, TRL 3-4), there is likely to be a rich commonality between the technology areas needed by HEDS and other NASA Strategic Enterprises. Moreover, in a few areas—particularly those related to planetary exploration and Earth-orbiting platforms—a still greater degree of commonality could exist. In these cases, technology maturation to TRL 5 within the crosscutting technology program may well be appropriate. In these areas, there is the potential for future research and technology partnerships between HEDS and the Space Science Enterprise. In particular, the HEDS Enterprise provides technology needs to and relies on the research and technology products of the NASA Crosscutting Technology Development Program, which is managed by the Space Science Enterprise.

8.2 Organization of HEDS Technology

The HEDS Enterprise comprises two NASA Headquarters offices: the Office of Space Flight and the Office of Life and Microgravity Sciences and Applications. In addition, the Office of Aero-Space Technology and the Office of Space Science play key roles in the development of technology for the HEDS Enterprise (as noted previously). Figure 8.2-1 illustrates the various participants in NASA's HEDS technology efforts, along with examples of some specific research and development investments for which they are responsible.

8.3 Summary of Major Elements of HEDS Technology

As noted previously, there are a wide variety of major elements of HEDS technology development, including a wide range from nearer term, low-risk investments to farther term, high-risk activities. These include: the X-38 program; the Advanced Human Support Technology program; the Advanced EVA Technology program; orbital debris measurement, modeling, and detection; other advanced projects activities; Space Shuttle upgrades; ISS research and technology development activities; and the Space Operations and Communications Technology program. The following subsections provide brief summaries of some of the major elements of the HEDS technology effort, focusing only on those research and development activities that are funded directly from HEDS. (Other HEDS-supporting research and development—for example, in the Office of Aero-Space Technology—is described in other sections of the NASA Technology Plan.)

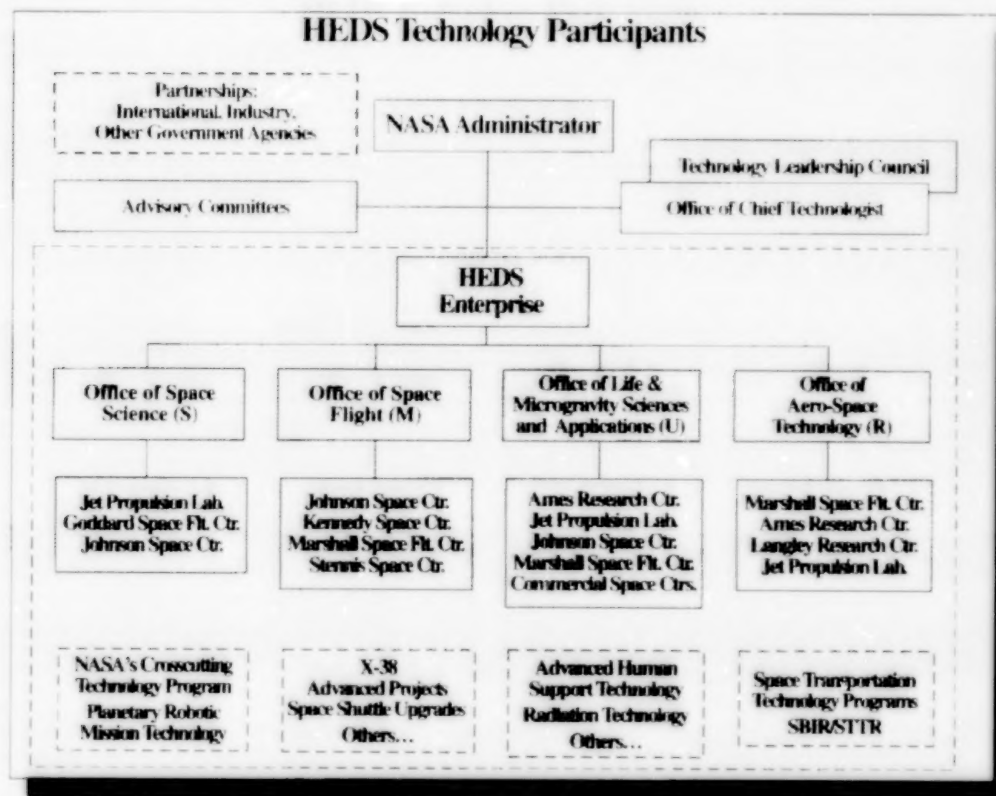


FIGURE 8.2-1. HEDS TECHNOLOGY DEVELOPMENT ORGANIZATION

X-38 Program

For safety reasons, a Crew Return Vehicle (CRV) is necessary for permanent human habitation of the ISS. The Russian Soyuz spacecraft will provide an interim CRV capability during the three-crewmember stage. The X-38 experimental vehicle project will allow HEDS to demonstrate the technologies and processes required to produce a CRV in a better, faster, cheaper mode.

Evaluations of the performance of the technologies of the X-38 systems are being conducted through a series of ground, air, and space tests. The X-38 design is based on the historical U.S. Air Force/Martin-Marietta X-24A lifting body research vehicle. The successful demonstration of the X-38 technologies is a precursor to the decision process to select a long-term CRV configuration for the ISS. Through cooperative arrangements that are under discussion with the European Space Agency (ESA), the Department of Defense, and the National Space Development Agency of Japan, NASA is seeking to find and develop commonality among space vehicles being developed for CRV and other requirements.

A wide variety of activities are being undertaken by the X-38 project, including the recent evaluation of prospective subsystem and system performance. A key element of the plan includes completion of the Atmospheric Test program in which two vehicles (131, 132) are being drop-tested from a B-52 to demonstrate full-lifting body control and parafoil control systems in various flight modes. Five atmospheric test flights of X-38 program Vehicles 131 and 132 are being

conducted. A third subscale atmospheric test vehicle with the identical shape of the operational vehicle will be added the X-38 program in FY 1998, and flight tests for this third atmospheric vehicle are scheduled for FY 1999. The construction of the first space vehicle (Vehicle 201) is also being initiated in 1998, as well as the purchase of the deorbit module for the planned X-38 orbital flight test. The primary structure (cabin and aft fuselage) will be fabricated, most subsystems will be installed and ready for integrated test, and some aeroshell panels with thermal protection system will be completed.

The second space test vehicle will be started in FY 1999, with a completion date of FY 2000. The aft fuselage, outer skin, and thermal protection systems were completed, and the first deorbit module was delivered. The integrated testing of Vehicle 201 will also begin in FY 1998.

An independent study will be initiated in FY 1998 to assess the applicability of the X-38 design as the ISS CRV, as well as a Crew Transfer Vehicle and other options that meet the ISS's crew rescue requirements. This study will inform the industry led future space launch trade studies described in the Section 9.

Advanced Human Support Technology Program

The goals of this program are to (1) demonstrate and validate full self-sufficiency in air, food, and recycling technology for use in space vehicles or planetary bases, (2) demonstrate and validate integrated, fully autonomous environmental monitoring and control systems, and (3) validate and incorporate human factors engineering technology and protocols to maintain high ground and flight crew skills during long-duration missions. The program includes advanced life support systems, space human factors, and advanced environmental monitoring and control.

Advanced Life Support. Recent accomplishments include (a) the development and delivery of a solid waste processing subsystem by NASA's Ames Research Center for evaluation in a 90-day closed-chamber life support test with four humans at NASA's Johnson Space Center; (b) the completion of a 336-day, closed-chamber wheat/potato shared atmosphere evaluation at NASA's Kennedy Space Center; (c) the completion of a 60-day closed-chamber ISS life support system with four humans at Johnson; (d) the reflight of the Electrolysis Performance Improvement Concepts Study on STS-84; and (e) the completion of facility preparations and the initiation of a 90-day, four-person closed-chamber life support systems test at Johnson. Ongoing advanced life support activities include: (a) the completion of a 90-day, four-person closed-chamber life support systems test; (b) the completion of first stage of Bioregenerative Life Support Systems Test Complex (BIO-Plex) facility construction; (c) the successful flight of the Two-phase Extended Evaluation in Microgravity flight experiment; (d) the completion of mixed cropping and the effects of recycling gray water; and (e) the initiation of Mars transit/habitation life support technology ground testbed (TransHab) facility outfitting.

Space Human Factors. Space human factors accomplishments include: (a) perceptual investigations of human thresholds for electronically produced visual data at Ames that have contributed to the data receipt and analysis of the Mars Pathfinder mission; and (b) operational analyses at Johnson that have contributed to ground controller interaction with automated processes, lighting models that have been developed to predict television camera and lighting interactions on orbit in support of Shuttle-Mir dockings and ISS assembly training, and the beginnings of a rapid prototyping lab-

oratory for advanced displays and controls in crewed vehicles that have been developed. Ongoing activities include: (a) the completion of the rapid prototyping laboratory that will become a major contributor to updates to ongoing programs as well as developing programs; and (b) visual, auditory, and perceptual research that will continue to investigate the thresholds of human interaction with onboard systems. Human-automation interactions and the definition of proper partitioning between the two will mature, crew accommodations evaluations and development for long-duration exploration will begin, and operational analyses of human-machine interfaces in ongoing and developing flight programs and ground analogs will address the resolution of emerging issues while gathering data for application to future long-duration exploration missions.

Advanced Environmental Monitoring and Control. Figure 8.3-1 shows the advanced environmental monitoring and control technology roadmap. Recent technology development accomplishments in this area include: (a) the testing of an advanced electronic nose during the 60-day, closed-chamber test at Johnson; and (b) the development of detailed program requirements by NASA, academia, and industry. Ongoing activities include a Space Shuttle flight test of electronic nose technology.

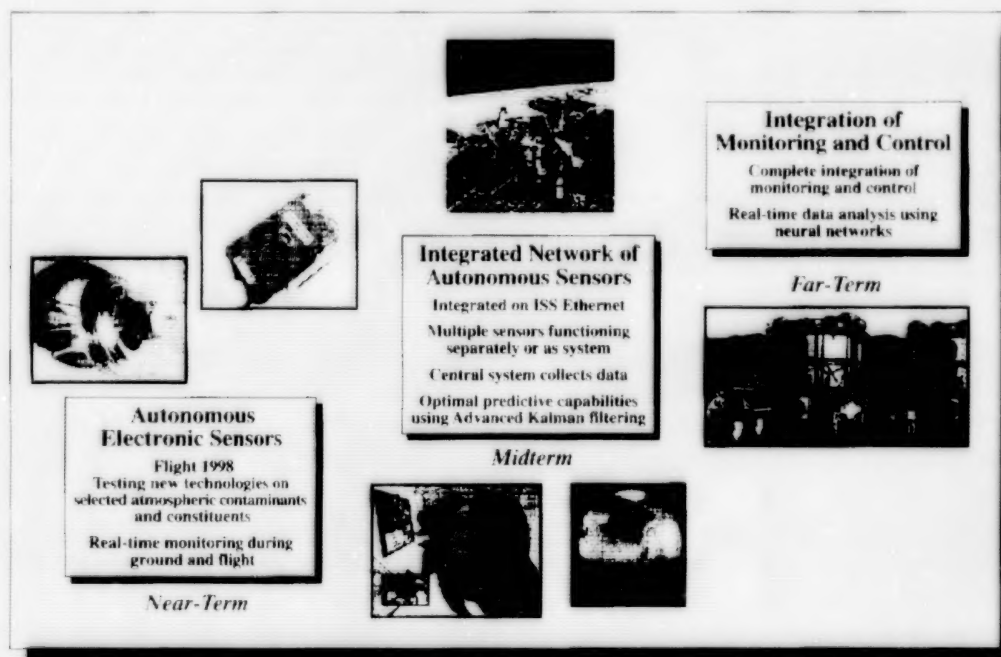


FIGURE 8.3-1. ADVANCED ENVIRONMENTAL MONITORING AND CONTROL TECHNOLOGY ROADMAP

Advanced EVA Technology Program

The primary goals of the Advanced EVA Technology program are to perform the scientific research and engineering development needed to mature technologies that enhance EVA crew safety, reduce EVA operational costs, and enhance capabilities to meet future space flight requirements. Programmatically, FY 1998 was a year of transition for this program; selected elements of the effort, which was part of the former Advanced Projects Office program, have been transferred to either the ISS program or the Space Shuttle program, as appropriate.

The advanced EVA program includes research and development to reduce the operational impact of decompression sickness, while increasing safety via a better understanding of the science involved. The research and development roadmap includes tasks to address environmental protection, EVA mobility, electronics integration, and EVA system integration with other space systems. The program is conducted using a mix of ground-based simulation and flight testing to prove the development approach. After 4 years of ground-based research and development, the program concludes with a 3-year task to demonstrate, on orbit, the new EVA technologies from a systems viewpoint. The program actively seeks partnering with industry and other Government agencies as well as the transfer of technology into the program from outside sources to accomplish the needed technology development.

By the end of 1998, advanced EVA gloves will be ready for flight tests to demonstrate on-orbit performance that incorporates increased mobility features and better thermal protection. Also, hardware for a new soft spacesuit configuration will be delivered for testing to determine the amount of mobility that can be incorporated into a soft suit configuration. Such soft suits hold the potential to be lighter weight and easier to stow. Finally, an advanced EVA system radiator will be ready for testing to demonstrate on-orbit cooling using a radiator instead of water sublimation in the real thermal environment.

Orbital Debris Measurement, Modeling, and Protection

The HEDS orbital debris effort supports projects that improve the safety of the Space Shuttle and the ISS by measuring, modeling, and mitigating the orbital debris environment. In addition, the activity includes an international cooperative program, jointly funded by the space agencies of Russia, Japan, China, and Europe, which seeks to develop a common understanding of the debris environment. This program also develops common practices for protecting spacecraft and mitigating the orbital debris environment. Programmatically, FY 1998 was a year of transition for this program; selected elements of the effort, which was a part of the former Advanced Projects Office program, also have been transferred to either the ISS program or the Space Shuttle program, as appropriate.

Recent and ongoing activities within the orbital debris program have been directed at measuring the orbital debris environment, developing debris growth mitigation measures, and enhancing spacecraft protection and survivability techniques. In FY 1998-99, additional measurements of the environment are being obtained from numerous Shuttle missions, providing invaluable data on the nature of the microdebris environment and its damage potential to manned spacecraft. The liquid metal mirror telescope was moved to Cloudcroft, New Mexico. Visual observations of debris particles as small as 10 centimeters in geostationary orbit are possible using this telescope. The Orbital Debris Radar Calibration Spheres flight demonstration, flown on the Space Shuttle, deployed three spheres and three dipoles that were used to calibrate the Haystack Orbital Debris Radar, optical telescopes, and other radar used to characterize the orbital debris environment.

Recently, the Haystack Auxiliary Radar and the Haystack Radar have continued to monitor the orbital debris environment for the ISS. Orbital debris will continue to focus on characterizing changes in the orbital debris environment as a function of time and on establishing measures for mitigation of debris growth trends. An international geostationary debris-observing program will be initiated, with participation from NASA, the European Space Agency, Russia, Japan, Australia,

and other spacefaring nations. Work will begin on the design of an EVA debris shield for protecting the ISS crews when they are exposed to the debris environment during an EVA. In addition, the Orbital Debris Collector, returned from *Mir* last year, is an experiment to collect in situ samples of the microdebris environment from the orbit of the ISS to understand the sources of this debris and thus enable effective steps to mitigate it.

Other Advanced Projects Activities

Various other activities continued at a minimal level during FY 1998, including technology studies relating to low-cost space launch, future spaceport operations, applications of miniaturization and nanotechnology to HEDS mission needs, and advanced information technology applications for HEDS, among others. One specific project that is being conducted involves the development of a partially inflatable advanced habitat system for future demonstration and possibly application on the ISS as well as other diverse missions.

Several flight experiment activities are being concluded. For example, analyses are being conducted of an aerogel flight test article, flown in 1997 on the *Mir* space station. Also, the International Space Welding Experiment will be flown with NASA-provided test samples as a joint Ukrainian-Russian payload to *Mir* to demonstrate the ability to perform contingency repairs to the ISS using an electron beam-welding device developed by the Paton Institute in the Ukraine. In addition, a small experiment, the Students for the Exploration and Development of Space Satellite (SEDSAT), is being planned for launch as a Delta II secondary payload. SEDSAT will serve as an amateur radio relay system and will collect multispectral remote-sensing data.

Space Shuttle

In addition to flying safely and making needed management changes, HEDS is implementing a continuing Safety and Performance Upgrades (S&PU) program intended to mature and infuse new technologies into the Space Shuttle program. The Space Shuttle upgrades activity is planned and implemented from a systemwide perspective. Individual upgrades are integrated and prioritized across all flight and ground systems, ensuring that the upgrade is compatible with the entire program and other improvements. New upgrade selection will be through the review process, with approval by the Associate Administrator for Space Flight, the Program Management Council, and the NASA Administrator. Implementation authority and responsibility will be delegated to the Lead Center Director for the Space Shuttle program, with the Shuttle Program Manager and the projects. Space Shuttle upgrades are developed and implemented in a phased manner supporting one or more of the following program goals:

- Improve Space Shuttle system safety and/or reliability
- Support the Space Shuttle program manifest/ISS
- Improve Space Shuttle system support
- Reduce Space Shuttle system operations costs

The phasing strategy is being coordinated with Reusable Launch Vehicle program management and other development projects to capture common technology developments, while meeting the Shuttle manifest. This phasing strategy should allow for the incorporation of additional, more

comprehensive upgrades to the Space Shuttle system while benefiting other programs and technologies. Candidate upgrades in the initial phases will use state-of-the-art technology and provide safety/reliability, supportability, and/or cost (improvement) advantages. Candidate designs in the initial phases maintain the current Shuttle mold lines and system/subsystem interfaces.

The S&PU effort includes the completion of selected projects, termed "Phase I" upgrades, that are designed to improve Space Shuttle safety and to improve payload-to-orbit performance by 13,000 pounds. This will allow the orbiter to achieve the orbital inclination and altitude of the ISS and support its assembly. All the Phase I upgrades are on track to meet the performance requirements of the first ISS assembly flight. "Phase II" upgrades that have been added to the effort are required to assure mission supportability into the next century.

The primary safety enhancement is the development and deployment of the Space Shuttle Main Engine (SSME) Block 2a/2, which doubled overall Shuttle ascent safety (for example, the Large Throat Main Combustion Chamber (LTMCC) and other improvements described below). In addition, a significant portion of the S&PU investment is dedicated to avoiding and preventing deleterious and costly effects of obsolescence while undertaking the challenge of reducing the costs of operations. For example, S&PU supports the replacement of the orbiters' cockpit displays with the Multifunction Electronic Display System (MEDS) replacing the Tactical Air Navigation System with GPS, upgrading the T-38 aircraft with maintainable systems, replacing elements of the launch site complex, upgrading major elements of the training facilities at NASA's Johnson Space Center, testing main engine components at NASA's Stennis Space Center, testing orbiter reaction control systems at the White Sands Test Facility, and replacing critical subsystems in the Kennedy Space Center facility complex.

In addition, S&PU addresses Shuttle supportability upgrades that will maintain availability of the Space Shuttle fleet for the foreseeable future. Space Shuttle program supportability upgrades are founded on the premise that safety, reliability, and mission supportability improvements must be made if the Shuttle system is to continue to provide safe and affordable operations into the next century. These upgrades will enable safe and efficient Shuttle operations during the ISS era while providing a robust testbed for advanced technologies and a variety of customers.

Orbiter Improvements. Orbiter improvements provide for modifications and upgrades to ensure the compatibility of the Space Shuttle vehicles with the new ISS operational environment. Orbiter weight reductions have been identified; operating experience or updated requirements allow selected items to be changed without impact to crew safety or mission success. The orbiter weight will be reduced by changing the exterior thermal protection materials on certain portions of the orbiter, changing the material on the "flipper doors" that provide a seal between the orbiter wing and its control surfaces, and developing lighter weight crew seats for the cockpit.

There have been several recent improvements in the Space Shuttle vehicle. For example, a fuel cell single-cell monitoring system was installed in response to fuel cell problems that had been encountered. The new monitoring system was developed and implemented in the first orbiter in less than 4 months. Other orbiter improvements include new digital autopilot software designed to reduce fuel consumption during deorbit and new launch trajectory software to increase performance margins and enable the deletion of the Bermuda tracking station for communications during

launch. The Solid Rocket Booster also received several upgrades designed to reduce the expense of recovering and refurbishing the boosters.

The MEDS upgrade will replace the current orbiter cockpit displays, which are early-1970's technology. The current displays, which provide command and control of the Space Shuttle, are "single-string" electromechanical devices that are experiencing life-related failures and are maintenance intensive. Difficulty in obtaining parts, some of which are no longer manufactured, is becoming more prevalent. The MEDS upgrade is a state-of-the-art, multiple redundant liquid crystal display system. MEDS will enhance the reliability of the cockpit display system, resolve the parts availability problem, and provide a much more flexible and capable display system for the crew. Secondary benefits of MEDS are reductions in the orbiter's weight and power consumption.

An effort to replace the orbiter's Tactical Air Command and Navigation System, which is the landing navigation system, with GPS began several years ago. This expansion includes an increased interaction of the GPS receiver with the orbiter backup flight software and outfitting two more orbiters with a GPS test receiver. A number of development flights are planned, with the first flight of a complete GPS system targeted for 1999.

Propulsion Upgrades. Space Shuttle propulsion upgrades are focused on expanding existing safety margins and reducing operational costs. The most complex components of the SSME are the high-pressure turbopumps. In reviewing the most critical items on the SSME that could result in a catastrophic failure, more than 14 of the top 25 are associated with the turbopumps. The current pumps' dependence on extensive inspection to assure flight safety have made them difficult to produce and costly to maintain. The Alternate Turbopump program has pursued for a decade the parallel development of both the High Pressure Oxidizer Turbopump and the High Pressure Fuel Turbopump to correct the shortcomings of the existing high-pressure turbopumps. This objective is achieved by using design, analytical, and manufacturing technology not available during development of the original components, applying lessons learned from the original SSME development program, eliminating failure modes from the design, implementing a build-to-print fabrication and assembly process, and providing full inspection capability by design.

For example, the Alternate Turbopump program's turbopumps utilize precision castings to reduce the total number of welds in the pumps by 100-fold. In another case, the LTMCC development has resulted in lower pressures and temperatures throughout the engine system, thereby increasing the overall Space Shuttle system flight safety and reliability. The LTMCC design incorporates new fabrication techniques to reduce the number of critical welds and improve producibility. High Pressure Oxidizer Turbopumps and the LTMCC have been successfully flown and are forecast to reduce the overall Space Shuttle ascent risk by a factor of two.

The Block 2 advanced SSME is scheduled to be flown in early 1999; it will incorporate the Alternate Turbopump program's High Pressure Fuel Turbopump. This engine improvement should yield a further increase in the overall engine durability, reliability, safety margin, and producibility. This is consistent with NASA's goals of decreasing failure probability and reduced Space Shuttle program costs.

Increased safety margins and launch reliability on the Space Shuttle have also been realized through the implementation of new sensors (temperature, pressure, and flow) for use in the SSME.

SSME history has shown that the engine is more reliable than the instrumentation system; however, a transducer failure could result in a flight scrub or an on-pad abort, a failure to detect an engine fault, or an in-flight abort. These sensor upgrades have been essential to improving the reliability of the Space Shuttle's launch capability.

The Super Lightweight Tank (SLWT) program is a result of NASA's desire to enhance the payload capability of the Space Shuttle system to support the ISS program. In FY 1996, the verification testing of the Aluminum Lithium Test Article was successfully completed. This test demonstrated the capability of the liquid hydrogen barrel section of the SLWT to withstand flight loads with sufficient margin. The SLWT completed final assembly and proof testing in January 1998 in preparation for delivery to Kennedy Space Center. A fully integrated tanking test was completed at Kennedy in May 1998, and the first flight of the SLWT was conducted in June 1998 on STS-91.

Flight Operations and Launch Site Equipment Upgrades. These upgrades support prelaunch and postlaunch processing of the four-orbiter fleet. Key enhancements funded in launch site equipment include:

- Replacing hydraulic pumping units that provide power to orbiter flight systems during ground processing
- Replacing 16-year-old ground cooling units that support all orbiter power-on testing
- Replacing communications and the tracking Ku-band radar test set for the laboratories in the Orbiter Processing Facility and High Bays that support rendezvous capability and the missions
- Working on communications and instrumentation equipment survivability projects that cover the digital operational intercom system, major portions of Kennedy's 17-year-old radio system, and the operational television system
- Improving the Space Shuttle operations data network that supports interconnectivity between Shuttle facilities and other Kennedy and offsite networks
- Replacing storage tanks and vessels for the propellants, pressurants, and gases
- Adding an improved hazardous gas detection system
- Adding fiber optic cabling and equipment upgrades

A new Checkout and Launch Control System (CLCS) is being implemented to upgrade the Shuttle launch control room systems with state-of-the-art commercial equipment and software in a phased manner to allow the existing flight schedule to be maintained. The CLCS will reduce operations and maintenance costs associated with the launch control room by as much as 50 percent and will provide the building blocks to support future vehicle control system requirements. The Juno and Redstone phases of the CLCS were delivered in FY 1997. In these phases, the initial integration platform was defined, the engineering platform was installed, and the interface with the math models was established. The Thor and Atlas phases are scheduled for completion in FY 1998. During these phases, the initial applications for the Orbiter Processing Facility will be developed, the math models will be validated, an interface to the Shuttle Avionics Integration Lab will be established, and hardware testing will be done. The Titan and Scout phases of the CLCS are planned for FY 1999, during which orbiter automated power-up will be developed, peripheral locations will be upgraded, and selected vertical testing will be done. For example, the CLCS was used for detailed monitoring of the new SLWT during the critical tanking test prior to its first flight on STS-91 (noted previously). In FY 2000, the Delta and Saturn phases will be accomplished,

which includes completion of all launch application development, completion of software certification and validation, and a complete integrated flow demonstration. By the end of FY 2000, Operations Control Room-I will be fully operating, followed by certification in FY 2001. The first Shuttle launch using the CLCS is scheduled for FY 2001, with full implementation to be completed 1 year later.

The Hardware Interface Modules, which are electrical command distribution systems that support the launch processing system at Kennedy, are more than 25 years old. The Hardware Interface Modules upgrade replaces all chassis and cards with state-of-the-art, "off-the-shelf" hardware to improve system reliability and maintainability. Production and installation should be complete in FY 1999.

Future Shuttle Upgrades. In 1997, a Phase III/IV portion of the upgrade program was envisioned (see Figure 8.3-2). Since that time, the Agency formed a Space Transportation Council to assess advanced transportation areas in both the Office of Space Flight and the Office of Aero-Space Technology. Technology needs studies were conducted by the Space Shuttle program in FY 1997 and FY 1998. In recognition of the value of close collaboration on the technology needs of future Reusable Launch Vehicles, lead responsibility has been consolidated within the Advanced Space Transportation program. The Space Transportation Council will provide management oversight and policy direction across the Agency's activities in this area. Potential major Shuttle upgrades will be examined under the "Future Space Launch" industry-led trade studies.

ISS Research and Technology Development Activities

The ISS is integral to the HEDS technology approach in two distinct ways. First, it will provide a platform for conducting technology research, maturation, and validation activities—for both NASA and industry. In addition, the ISS will undertake the development and validation (typically on the Station) of technologies associated with and required for future "upgrades" of baseline ISS systems.

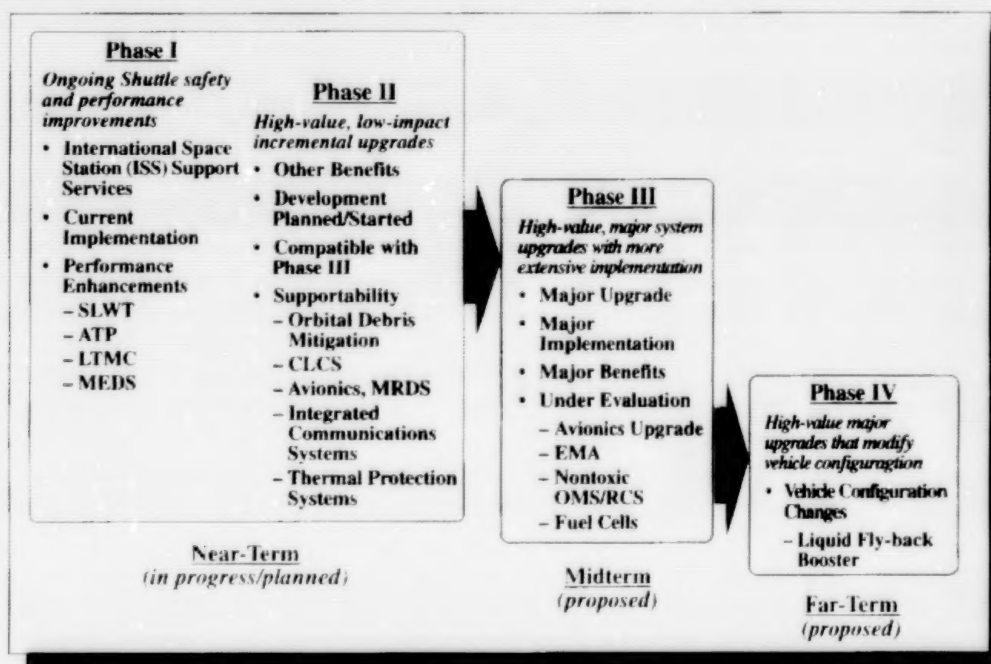


FIGURE 8.3-2. SPACE SHUTTLE UPGRADE TECHNOLOGY ROADMAP

Advanced Human Support Technology. One area that the ISS program is testing and validating is the advanced human support technology. The goals include the definition, development, and testing of advanced technology hardware and processes in support of humans-in-space engineering and life support and EVA. Specific areas of potential technology research that have been identified include closed-loop life support systems (carbon dioxide reduction and O₂ generation), biological water recovery, advanced telemetric biosensors, and wearable computers. The purpose of the advanced human support technology research and technology development facility on the ISS will be to identify, develop, and perform flight demonstration, testing, and validation of selected advanced technologies consistent with space and life sciences and the NASA Strategic Plan. These flight experiments will demonstrate miniaturization, lower power consumption, high reliability, ease of use, and cost-effectiveness for technologies that play a role in life support, environmental monitoring and control, biomedical research and countermeasures, crew health care, and Eves. The advanced human support technology experiment will provide a means for taking advanced technologies, which may originate within or outside NASA, to levels of maturity beyond what could be accomplished through ground testing alone. This effort will also enable rapid accommodation of advanced technologies into operational systems on the ISS.

Biomedical Research. Biomedical research activities include the Human Research Facility, the Crew Health Care Subsystem, and the associated payload development. Human Research Facility hardware will enable the standardized, systematic collection of data from the ISS's crewmembers that the medical and research community will require to assure crew health. These basic research activities will provide a foundation for future technology efforts; once verified in orbit, the Human Research Facility will be used to conduct basic and applied human research and technology experiments.

Microgravity Research. Microgravity research activities will support a broad range of activities spanning the spectrum from basic research to applied research to technology development. These will include development of several research and development facilities for the ISS: the Fluids and Combustion Facility, the Materials Science Research Facility, the Biotechnology Facility, and the Low-Temperature Microgravity Physics Facility. In the future, various payloads will be developed and flown. For example, the Biotechnology Facility will support research in the areas of protein crystal growth and cell tissue cultures, including studies on the maintenance and response of mammalian tissue cultures in a microgravity environment. Similarly, the Fluids and Combustion Facility will support research on interfacial phenomena, colloidal systems, multiphase flow and heat transfer, solid-fluid interface dynamics, and condensed matter physics, as well as the definition of the mechanisms involved in various combustion processes in the absence of strong buoyant flows.

The Materials Science Research Facility, formerly the Space Station Furnace Facility, will be used to study the underlying principles necessary to predict the relationships of synthesis and processing of materials to their resulting structures and properties. It is anticipated that cooperative efforts with the international science community will assist in the development of some discipline-specific furnace modules for use by the U.S. science community, thus leveraging the hardware development investments undertaken by NASA. The objective of the Low-Temperature Microgravity Physics Facility is to investigate the fundamental behavior of condensed matter without the complications introduced by gravity; primary research in this facility will study the universal properties of matter at phase transitions and the dynamics of quantum fluids.

Commercial Research. NASA's commercial research programs for the ISS will take advantage of the new opportunities for space flight operations provided by the ISS and a distinctly new operating environment. Among other activities, the commercial research programs for the ISS will concentrate on commercial protein crystal growth and plant growth research. The commercial protein crystal growth activities for the ISS are under way at the Center for Macromolecular Crystallography, and plant growth research is occurring at the Wisconsin Center for Space Automation and Robotics, the Center for Bioserve Space Technologies, and their industrial affiliates. In addition, NASA's Johnson Space Center has formalized a cooperative agreement with the Texas Engineering Experiment Station of Texas A&M University for the development and implementation of a Commercial Space Center for the development of engineering research and technology payloads for the ISS.

Engineering Research and Technology. A variety of engineering research and technology payloads are being supported by the ISS in pressurized laboratories or at external payload accommodations (truss attach sites). The Engineering Research and Technology (ER&T) program will maximize the use of the ISS as a unique on-orbit laboratory and technology testbed. Advanced technologies will be tested and demonstrated in support of other NASA space technology development objectives and to foster partnerships with other U.S. Government, industry, and academic communities. The ER&T program will identify and define innovative technology concepts, develop these concepts into flight experiments and technology demonstrations, and perform the necessary laboratory-scale investigations and demonstrations aboard the ISS, to validate the physical characteristics of concepts and the functional operability of demonstration hardware. The ER&T program will promote the fast-track implementation of these experiments and technology demonstrations and will support ISS preplanned product improvement objectives and recommendations. ER&T payloads current being pursued include the integrated Energy Storage and Attitude Control Experiment (flywheel), Optical Communications Demonstration and High-Rate Link Facility, Photovoltaic Engineering Testbed, Micron Accuracy Deployment Experiments, Control of Flexible Construction Systems, Payload Tutor (internal robot), and Inspector (free-flying inspection platform).

ISS Preplanned Improvements. A series of low-level technology studies, research and development, and maturation activities related to future preplanned product improvement for the ISS are being conducted during FY 1998 and planned for FY 1999. These efforts address key areas of functionality in which evolutionary improvements could enable significant enhancements in research productivity, operations' performance, and systems and operations safety, and significant cost reductions could be enabled in part by a focused process for commercialization of preplanned product improvement candidates. A roadmap addressing ISS technology improvement needs, ISS payload technology improvement needs, and synergistic technology needs in support of other NASA space technology objectives has been developed and will be updated as required. An example of preplanned product improvement-supported technology improvements is the application of advanced flywheel technology for ISS on-orbit power storage requirements and potential improvements in the ISS communications system with advanced antenna technology.

Space Operations and Communications Technology Program

As mentioned in Section 5.2, within HEDS, the Space Operations Management Office (SOMO) conducts the Space Operations and Communications Technology program (SOCTP). The mission

of SOMO is to implement the Agency's space operations goals, while successfully providing services which enable Strategic Enterprise mission execution.

To enable frequent, affordable, capable space missions in the 21st century, key technologies will have to be developed and flight validated that can contribute to lowering life-cycle costs and increasing scientific returns. Reliable telecommunications services are needed to ensure that the goals of NASA's exploration, science, and research and development programs are met cost-effectively. Innovative microelectronics and advanced flight computing technologies are required, as well as concepts for autonomous spacecraft guidance, navigation, tracking, and control. Through the use of "intelligent" and automated ground and flight systems, mission operations and costs will be reduced. New concepts and techniques for data transfer, handling, and storage are being pursued to complement the advancements in high-speed data communications networks.

Also, as NASA moves toward using more commercial services, advanced techniques and products are being planned that support low-, middle-, and geosynchronous Earth orbit commercial satellite networks for integrated, fixed, transportable, and mobile broadcast and/or wireless communications and information services. In addition, as a participating agency of the National Search and Rescue Plan and a member of the Interagency Committee on Search and Rescue, NASA supports technologies and the application of aerospace technology to the search, rescue, survival, and recovery of individuals trapped by hazardous situations.

The SOCTP is structured to meet SOMO's wide array of customers' technology needs effectively. It consists of five elements: strategic planning, commercial satellite communications and operations, deep space communications and operations, Government-unique near-Earth orbit communications and operations (with subelements of unmanned and manned missions), and terrestrial data distribution. Key technology areas include microcommunications and navigation systems, flight/ground system autonomous operations, advanced communications and data handling techniques and systems, and Government and commercial interoperable communications systems. Meeting the strategic needs of the NASA Enterprises, while reducing operations costs, will be accomplished by consolidating and integrating operations across the Agency, emphasizing the use of technology, and increasing standardization and interoperability.

In support of this strategy, the SOCTP goals are to (1) reduce the cost of NASA space operations, (2) provide enabling data and mission services to the NASA Enterprises, and (3) advance U.S. industry leadership in commercial satellite communications. Currently, there are many activities under way that support these goals, such as strategic planning involving the commercial satellite communications industry members, the handling of interoperability issues through the use of the Advanced Communications Technology Satellite (ACTS), satellite component development, optical communications component development, Ka-band experiments, and the prototyping of expert systems for use in unattended operations. Future projects are aligned with the SOCTP goals and the technology thrust areas, as shown in Table 8.3-1.

TABLE 8.3-1. FUTURE PROJECTS

<i>SOCTP Goals</i>			
	<i>Reduce the cost of NASA space operations</i>	<i>Provide enabling data and mission services to the NASA Enterprises</i>	<i>Advance U.S. industry leadership in commercial satellite communications</i>
Thrust Areas	Commercial Asset Utilization	High-Performance Communications	Hybrid Network Ubiquity
	Interoperability and Standardization	Intelligent Systems and Autonomy	Precompetitive Research and Technology to Open New Markets
	Flight and Ground System Automation	Innovative Mission Information Systems	Space Environment Characterization
	Process Innovation Tools		

8.4 Relationship Between HEDS Technology and Goals

The HEDS Enterprise intends to implement and support research, technology, and systems development projects in pursuit of its four broad strategic goals, which are to:

- Explore the role of gravity in physical, chemical, and biological processes
- Prepare to conduct human missions of exploration
- Continue to open and develop the space frontier
- Aggressively seek investment from the private sector

In pursuit of its strategic goals, the HEDS Enterprise undertakes several technology research and development efforts. In the case of near- and midterm technology development needs, HEDS strategic goals and its research and development investments are related through specific, typically large-scale programs and/or projects. The Space Shuttle program and the ISS program and related efforts characterize the approach. When addressing the Enterprise's longer term objectives, strategic technology investments are planned and implemented that may bear no current relationship to a specific existing project, but that are nevertheless traceable to one or more of the HEDS strategic goals. For example, the longer term investments being undertaken in the Advanced Space Transportation program typify this aspect of the overall investment.

8.5 Determination of HEDS Technology Investments

In general, HEDS technology investments are focused around integrated systems analysis studies that examine benefits, risks, and costs for various concepts and technologies. These include mission architecture studies, driven by HEDS strategic goals, which lead to specific mission plans and development projects, as well as focused technology investment planning, including technology testbeds and flight demonstrations, and technology development programs. Figure 8.5-1 depicts this general approach of how HEDS technology investments are determined.

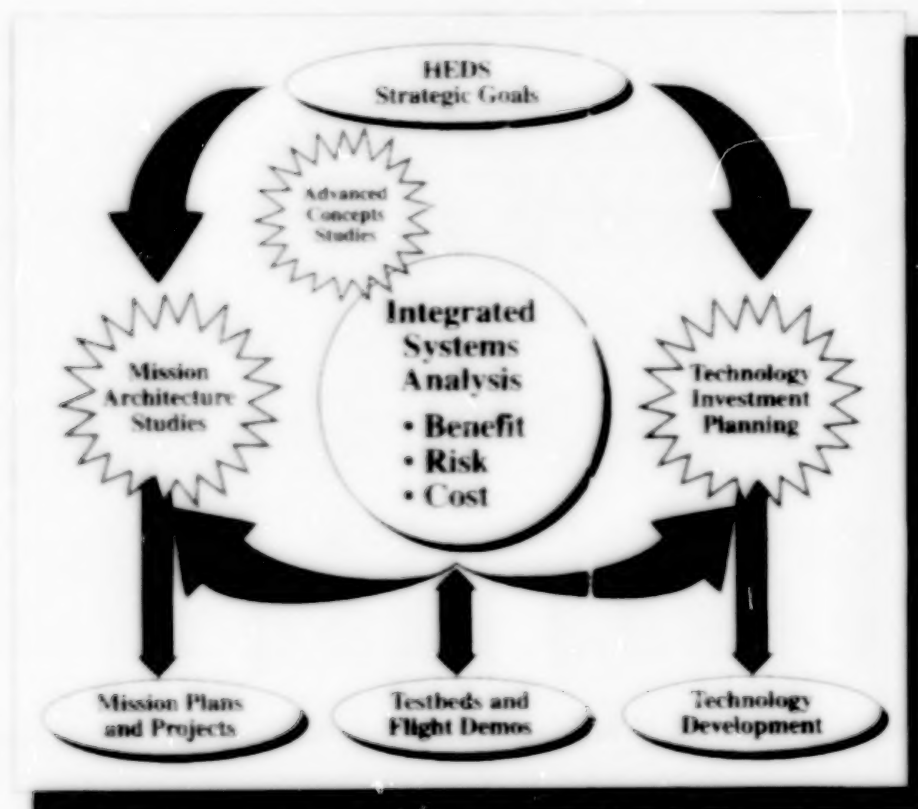


FIGURE 8.5-1. HEDS TECHNOLOGY INVESTMENT DEFINITION

In addition, HEDS takes into account a number of "guides" for technology investment decision making, including:

- Balance in time
 - There should be an appropriate balance between the nearer and farther term
- Balance in technical risk
 - There should be an appropriate balance between research and technology investments relating to the lesser and greater technical risk technologies
- Balance in addressing HEDS strategic goals
 - There should be an appropriate balance among investments relating to the several HEDS strategic themes
- In rough order of priority, investments will be made in technologies that dramatically:
 - Reduce the cost of future HEDS missions and projects
 - Increase the level and the quality of the scientific and other accomplishments of HEDS and human explorers
 - Increase the potential economic returns from the commercial development of space and in all cases
 - Enhance our ability to assure human health and safety in future HEDS missions
 - Can be applied in more than one of HEDS strategic goals



9.0 Aero-Space Technology Programs

9.1 Enterprise Approach to Technology

The "Three Pillars for Success" and their accompanying "Enabling Technology Goals," were presented in Section 3.4. The Aero-Space Technology Enterprise's research and technology supports these pillars and objectives by providing a foundation to:

- Develop advanced technology concepts and methodologies for application by industry
- Build focused programs to address selected national needs
- Respond quickly to critical safety and other issues
- Provide facilities and expert consultation for industry during product development and deployment and for other Government agencies

The robust technology candidates identified in the strategic planning process are pursued through programs organized by customer class and managed at a NASA Center. The applicability of the technologies to the goals is documented and tracked on goal investment strategy roadmaps by the strategic goal managers at NASA Headquarters.

9.2 Organization and Structure of the Enterprise Technology Program

The balance between Base Research and Technology (R&T) programs and Systems Technology programs is important in developing the Office of Aero-Space Technology strategy to meet its three pillar goals and the 10 Enabling Technology Goals. Because we are unable to predict how

one might achieve the stretch goals the Enterprise wishes to reach in 25 years, the right combination of fundamental research and advanced development is an important factor in making strategic investments. As depicted in Figure 9.2-1, the Base R&T program pursues the 25-year goal by developing a broad mix of long-term, high-risk, high-payoff technologies providing many potential options for achieving the goal. It does so by attacking the fundamental and barrier issues critical to achieving the goals. The nature of the technology development determines whether the technology transitions to systems technology programs or directly to the customer. The Base R&T program provides the basis for future Systems Technology programs.

The Systems Technology programs pursue and mature promising, high-payoff technologies. Aligned with critical issues to achieving stretch goals, the products of these programs are technologies raised to a readiness level appropriate for handoff to customers in other Government agencies or industry. The programs are planned with key decision points to provide opportunities to integrate key technologies developed within the Base R&T program and to strategically revector the program.

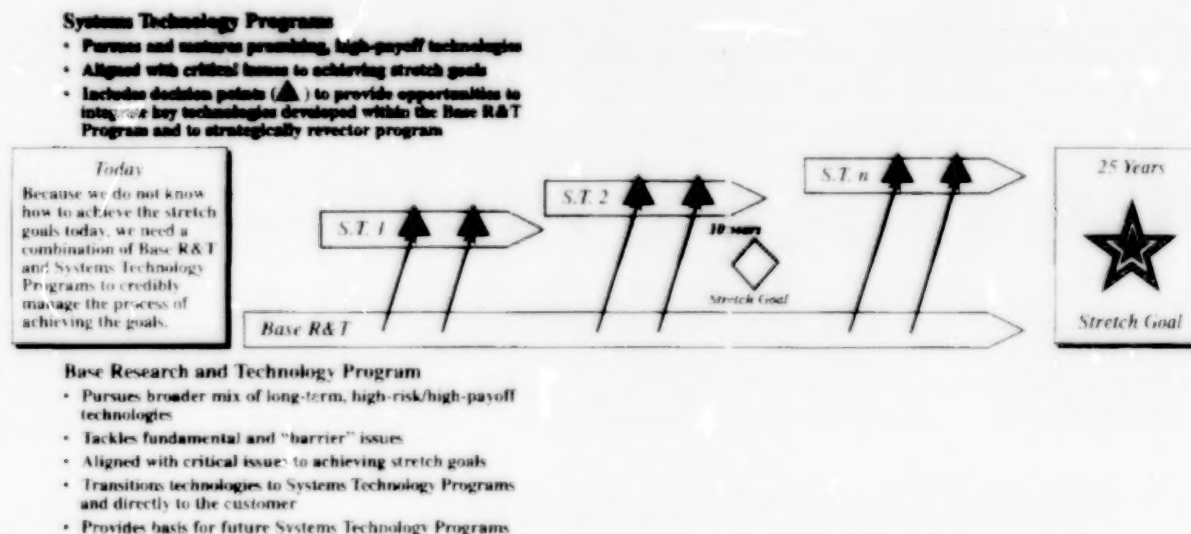


FIGURE 9.2-1. AERO-SPACE TECHNOLOGY ENTERPRISE TECHNOLOGY PROGRAM STRATEGY

The Aero-Space Technology Enterprise programs consist of a R&T Base program that addresses fundamental knowledge and long-term opportunities, a series of Aeronautics Systems Technology programs that seek to capitalize on such opportunities with concentrated efforts, and a Space Transportation Research and Technology program that addresses the issues of affordable access to space. These programs are depicted in Figure 9.2-2. In addition, a Commercial Technology program and the Small Business Innovative Research (SBIR) program reach out to industry (see Section 10).

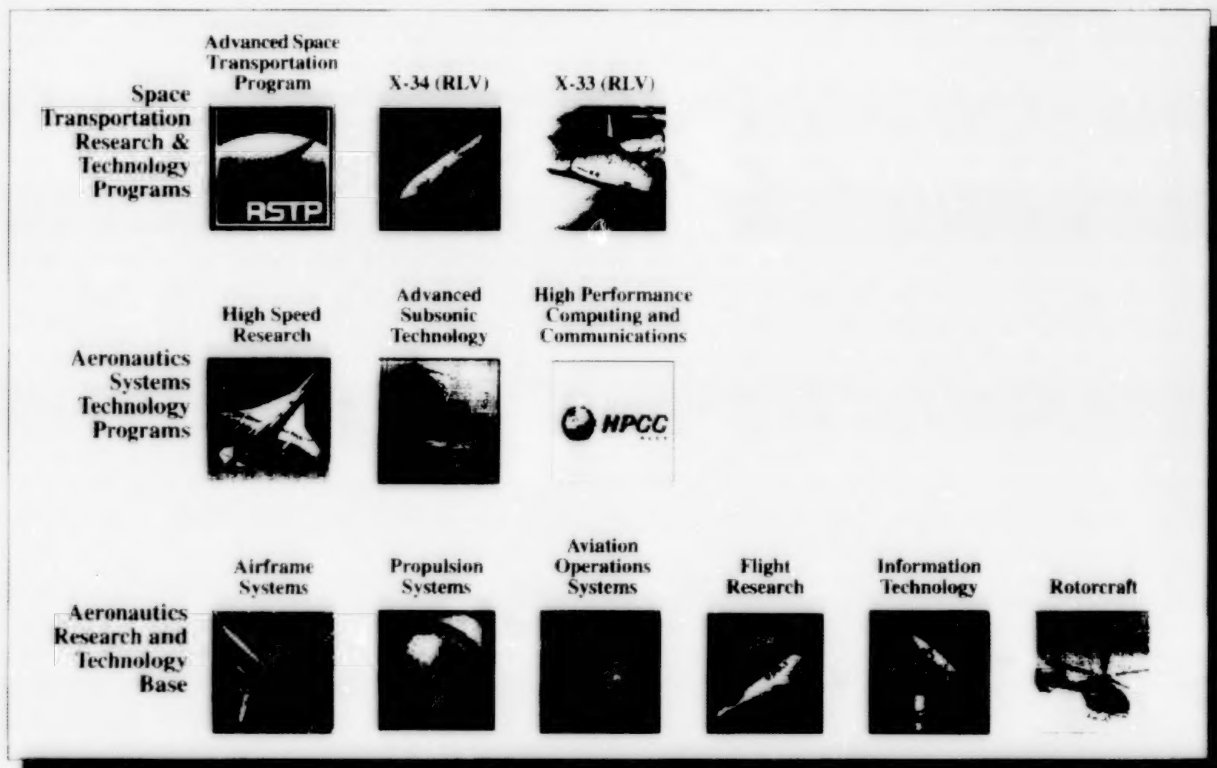


FIGURE 9.2-2. CURRENT AERO-SPACE TECHNOLOGY PROGRAM PORTFOLIO

Aeronautics Research and Technology Base

The Aeronautics Base R&T program consists of six systems-oriented customer-driven programs that serve the needs of the full range of aeronautical vehicle classes. These are continuing programs providing the research foundation for the Enterprise. Each is managed at one of the "aeronautics" Field Centers and encompasses efforts across Center boundaries. The six Base R&T programs and their areas of technology development are:

- *Information Technology*—computational tools and integrated systems for the design and manufacture of flight vehicles and systems
- *Airframe Systems*—conceptual design, aerodynamic and structural design and development, flight crew station design, airborne systems design and testing, and other areas for application to all fixed-wing atmospheric flight vehicles
- *Propulsion Systems*—efficient, safe, affordable, and environmentally compatible propulsion system technologies for subsonic and high-speed transports, as well as general aviation and high-performance aircraft
- *Flight Research*—tools and test techniques for all classes of aircraft, including subsonic and supersonic transports and remotely piloted, high-performance, and hypersonic aircraft
- *Aviation Operation Systems*—communications, navigation and surveillance systems, air traffic management, relevant cockpit systems, operational human factors, and weather and hazardous environment characterization and avoidance systems
- *Rotorcraft*—safe all-weather operations, low-noise technologies, and reduced manufacturing costs for both helicopters and tiltrotors

Aeronautics Systems Technology Programs

The Aeronautics Systems Technology programs were established to address selected national needs. Based on clearly defined customer requirements, the deliverables, critical program decisions, and completion dates of these programs were developed to raise the technology readiness to sufficient levels to allow for potential application. The current focused programs are:

- *High Performance Computing and Communications (HPCC)*—contributions to broad Federal efforts while addressing Agency-specific computational problems called “Grand Challenges”:
 - Computational AeroSciences to enable multifold improvements in the performance of air and spacecraft design tools such as computational fluid dynamics and structural analysis
 - Earth and Space Sciences to demonstrate TeraFLOPS systems performance to further our understanding and ability to predict the dynamic interaction of physical, chemical, and biological processes affecting Earth, the solar-terrestrial environment, and the universe
 - Remote Exploration and Experimentation to develop low-power, fault-tolerant, high-performance, scalable computing technology for a new generation of microspacecraft
 - Learning Technologies to accelerate the innovative distribution of technologies to the American educational community through NASA science, engineering, and technology contributions
- *High Speed Research (HSR)*—airframe and propulsion technologies that U.S. industry needs to enable a decision on aircraft production of an environmentally compatible and economically competitive High Speed Civil Transport (HSCT) for the 21st century
- *Advanced Subsonic Technology (AST)*—high-payoff technologies to enable a safe, highly productive global air transportation system that includes a new generation of environmentally compatible, operationally efficient U.S. subsonic aircraft (The critical needs were selected on the basis of industry–Federal Aviation Administration (FAA) technology requirements to provide a focused and balanced foundation for U.S. leadership in aircraft manufacturing, aviation system efficiency and safety, and protection of the environment.)

Space Transportation Research and Technology Programs

The Aero-Space Technology Enterprise is taking a three-tiered approach to space transportation technology development, as shown by Figure 9.2–3. The base tier is represented by the Space Transportation Research and Technology program (ASTP) of crosscutting, high-payoff technologies that range from the exploratory research of emerging technologies (core technologies) to the development and maturation of technologies for integration into flight demonstration projects (focused technology). The ASTP projects are aligned to support both the near- and far-term goals of Earth-to-orbit systems as well as provide the enabling capability to achieve the in-space transportation goal.

The second and third tiers are composed of flight demonstrations. The strategy behind these tiers is to validate incrementally the technologies in “real-world” operating environments and to demonstrate streamlined management and operational procedures that can dramatically reduce launch system costs. Ground tests *simulate* technology in its ultimate real-world application, but the “threat of flight” forces the project team to understand that each component, and team member,

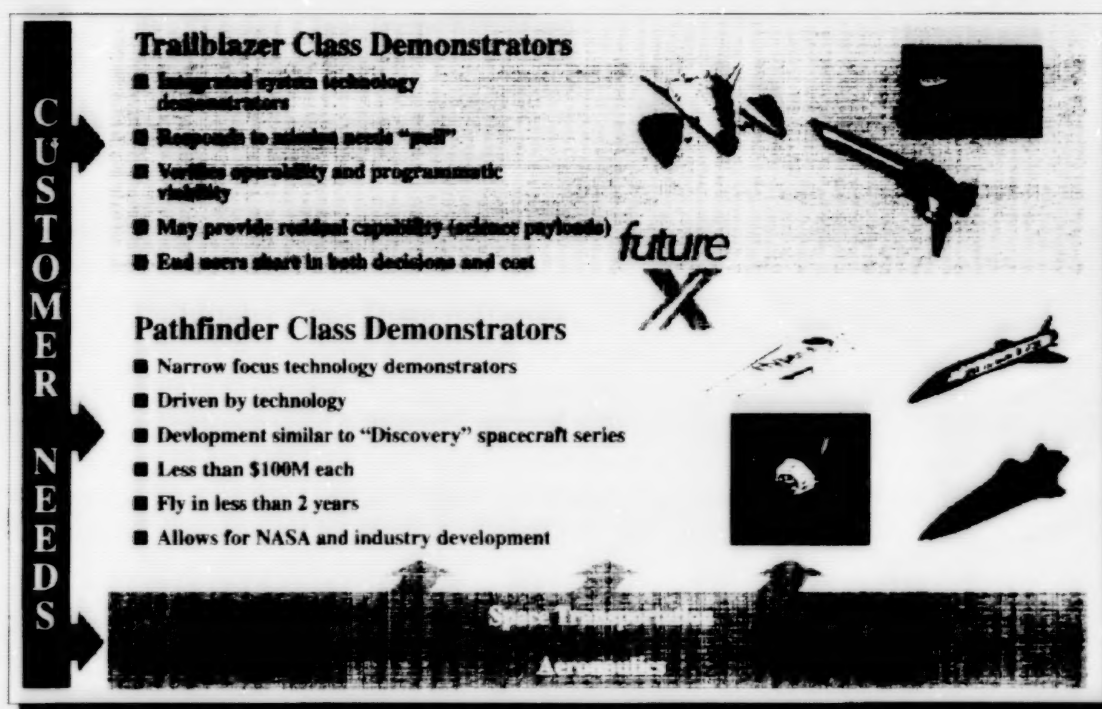


FIGURE 9.2-3. THREE-TIERED TECHNOLOGY MATURATION APPROACH

must function properly as an integral member of the overall flight system. This approach requires a maturity level in the technology development that cannot be provided in any other test environment.

The second tier is represented by small, narrowly focused flight demonstrations to validate technologies that must be flown in a real-world operational environment to ensure their application to existing and future space transportation systems. These "Pathfinder Class" X-vehicle demonstrators serve to push state-of-the-art technologies that have multiple applications to missions across the NASA Enterprises, other Federal agencies, and commercial customers. The X-34 and Hyper-X flight demonstration programs are examples of this area.

The third tier represents integrated system flight demonstrations to validate systems concepts that have the potential for achieving the near-term and far-term goals for Earth orbital and in-space transportation systems. This "Trailblazer Class" flight demonstrators respond to a strong mission needs pull and, where appropriate, involve significant industry leadership and involvement. A current example of this area is the X-33 program, which is focused on demonstrating the technologies for an order-of-magnitude reduction in launch costs. The second and third tiers of focused flight demonstrations make up the Reusable Launch Vehicle (RLV) portion of ASTP.

The Future-X projects are currently being defined based on inputs from the Joint NASA-Air Force Future Spacelift Requirements Study, NASA laboratories, and industry partners. The Future-X projects are envisioned to continue the demonstration of low-cost space transportation systems into the next millennium and could fly by 2001. The next Future-X configuration, technology, and scope remained open until the fall of 1998. Numerous technologies will also be pursued in the core technology program aimed at a configuration downselect in 1999, corresponding with the RLV full-scale development decision.

9.3 Elements of the Enterprise Technology Program

Aeronautics Research and Technology Base

Information Technology Program. The goal of the Information Technology program is to perform leading-edge research in advanced computing systems and user environments, revolutionary software technologies, and pathfinding applications that enable the achievement of NASA's missions in aeronautics and space transportation. Accomplishing this goal will require developing and demonstrating advanced technology concepts and methodologies, providing advanced validated tools and techniques, responding quickly to critical national issues, and providing the basis on which future focused programs are built. The program is built around three investment areas—Integrated Design Technology, Software Technology, and Advanced Computing Technology—which cover the elements in Figure 9.3-1.

TABLE 9.3-1. INFORMATION TECHNOLOGY INVESTMENT AREAS

<i>Integrated Design Technology</i>	<i>Software Technology</i>	<i>Advanced Computing Technology</i>
Analytical Tools and Environments for Design	Intelligent System Controls and Operations	Advanced Computing, Networking, and Storage
Integrated Instrumentation and Testing	Software Integrity, Productivity, and Security	

Table 9.3-2 shows the goals of the Aero-Space Technology Enterprise supported by these investment areas.

Integrated Design Technology. The objectives of the Integrated Design Technology investment area are to provide enabling technologies to radically reduce aircraft development time and cost, enable more comprehensive design optimization assessments, and expedite the aircraft certification process. The products are validated interdisciplinary and variable complexity analysis and design systems for aircraft and propulsion systems, and components to enhance performance, safety, and efficiency and affordability. This will be done by integrating the disparate design technologies through a suite of information system technologies.

A major focus of the Analytical Tools and Environments for Design project is the access by the aerospace design team to the wealth of heterogeneous design data. The data and their dissemination, integration, and conversion to knowledge need to be generated in as near real time as possible, with strong interfaces among instrumentation and computational capabilities, test site operational systems, and the design team.

TABLE 9.3-2. INFORMATION TECHNOLOGY SUPPORT OF ENTERPRISE GOALS

<i>ASST Goal</i>	<i>Integrated Design Technology</i>	<i>Software Technology</i>	<i>Advanced Computing Technology</i>
Reduce accident rate		✓	
Reduce emissions			✓
Reduce noise levels			✓
Triple throughput		✓	
Reduce cost of air travel	✓	✓	✓
Reduce travel time			✓
Design tools/X-aircraft	✓		✓
Reduce cost to orbit	✓		✓
In-space transportation	✓		✓

Within Integrated Design Technology, sharing the design data is paramount but gathering the high-confidence experimental data is equally important. The Integrated Instrumentation and Test Systems project will provide the foundation and backbone of this experimental design information and data gathering in the Information Technology program. To support the architecture of the information system with the desired broad information and data generation capability, the Integrated Instrumentation and Test Systems project is focusing on key implementations and demonstrations of technology applications in the following product areas: integrated instrumentation suites with test facility data and control systems, advanced instrumentation and test techniques to understand system performance and to compare and validate the computational fluid dynamic models, and complete remote access to the integrated knowledge sources associated with the test processes and data base information.

Software Technology. The specific objective of the Software Technology investment area is to enhance the safety and security of the National Airspace System (NAS) through the development of technologies for systems control and operations, as well as flight-critical software systems. The two projects within this investment area that support this objective are Intelligent System Controls and Operations and Software Integrity, Productivity, and Security. The products of this area include demonstrations of flight and propulsion control and data-sharing technologies and demonstrations of reduced software development time and cost while ensuring the safety and security of flight-critical software systems and information integrity within the NAS.

The Intelligent System Controls and Operations project seeks dramatic reduction in system and subsystem development cost and time of a wide class of aerospace vehicles. Meeting this objective requires technologies that will reduce major causes of accidents in flight-critical, human error, weather, and systemwide monitoring aspects within the NAS. Commercial transports, high-performance military aircraft, hypersonic vehicles, remotely piloted or unmanned concepts, rotorcraft, RLV's, and autonomous planetary aircraft will benefit from the developments of this project. The approach is to leverage information technologies and core competencies in soft computing and computational intelligence.

The Software Integrity, Productivity, and Security element will exploit new and emerging technologies to ensure the security, authenticity, confidentiality, and reliability of the information

transferred between and among human operators (such as pilots, air traffic controllers, and ground personnel) and automated systems. This research includes formal methods for requirements and design specification, automated code generation, high-assurance design techniques, secure communications systems, and appropriate verification and validation methods for these new technologies.

Advanced Computing Technology. The goal of this investment area is driven by the need to achieve a new plateau in the use of computers for aerospace design—to demonstrate dynamic supercomputing systems capable of greater performance at lower cost. Advanced Computing, Networking, and Storage responds to the requirements of the Aero-Space Technology Enterprise by investing in simulation-based approaches to aircraft design, manufacture, and operation. The objectives of Advanced Computing, Networking, and Storage are: (1) act as a pathfinder in advanced, large-scale, affordable computational capability through the systematic incorporation of state-of-the-art improvements in computer hardware and software technologies; (2) partner with key applications projects in aerospace design, production, and operation to evaluate and improve system performance, while providing research results for the applications community; and (3) pioneer radical new approaches to achieving higher performance systems.

Airframe Systems Program. The primary objectives of the Airframe Systems program are to develop advanced technology concepts and methodologies, provide advanced tools and techniques, respond quickly to critical national issues, and provide the basis on which future systems technology programs are built. The program is conducted in cooperation with U.S. industry, the FAA, the Department of Defense, and the academic community. The six major investment areas in the Airframe Systems program and their projects are listed in Table 9.3-3.

Table 9.3-4 shows the Aero-Space Technology Enterprise goals supported by these investment areas.

Advanced Vehicles Concepts. This investment area pioneers the development of advanced technology and advanced vehicle concepts. Advanced technology concepts are assessed for their potential benefits, and the vehicle concepts are evaluated to determine the technologies that are required for their development. The technology concepts may be demonstrated by modifying existing aircraft or by including them on new experimental aircraft.

The goals of the Revolutionary Concepts project are to accelerate the identification of technology applications and vehicle concepts that offer revolutionary capabilities to meet and exceed the stretch goals of the Aero-Space Technology Enterprise. Technologies developed by this and other programs in the Enterprise will be integrated to investigate barrier issues.

An urgent national need exists for more reliable, lower cost space launch capability, as well as aircraft and/or missiles with global response capability to provide U.S. defensive forces with a significant edge. The Hyper-X experimental aircraft project is demonstrating and validating technologies, experimental techniques, and computational methods and tools for design and performance predictions of a hypersonic aircraft with an airframe-integrated dual-mode scramjet propulsion system to meet those needs.

TABLE 9.3-3. AIRFRAME SYSTEMS INVESTMENT AREAS

<i>Advanced Vehicle Concepts</i>	<i>Tools and Test Techniques</i>	<i>High-Performance Aircraft</i>	<i>Safety</i>	<i>Breakthrough Technologies</i>	<i>Systems Analysis</i>
Revolutionary Concepts	Airframe Systems	Aircraft Tactical Technology	Error-Proof Flight Deck and Aircraft Electronic Systems	Futuristic Airframe Concepts and Technologies	Office of Aero-Space Technology Program Assessments
Hyper-X	Concept to Test	from Advanced Controls			
	Alternate Cooperative Capacity, Efficiency, and Safety Solutions	Advances through Cooperative Efforts	Total Aircraft Management Environment	Integral Airframe Structures	Technology Trade Studies
	Methods for Affordable Design	Revolutionary Military Aircraft Technologies	Airframe Airworthiness Assurance	Aircraft Morphing	
				Revolutionary Airframe Noise and Emissions Reduction	
				Advanced Subsonic Transport Aircraft Research	
				Breakthrough Innovative Technologies	

TABLE 9.3-4. AIRFRAME SYSTEMS SUPPORT OF ENTERPRISE GOALS

<i>Enterprise Goal</i>	<i>Advanced Vehicle Concepts</i>	<i>Tools and Test Techniques</i>	<i>High-Performance Aircraft</i>	<i>Safety</i>	<i>Breakthrough Technologies</i>	<i>Systems Analysis</i>
Reduce accident rate				✓		✓
Reduce emissions	✓	✓			✓	✓
Reduce noise levels	✓	✓			✓	✓
Triple throughput						✓
Reduce cost of air travel	✓	✓			✓	✓
Reduce travel time						✓
Invigorate general aviation						✓
Design tools/X-aircraft	✓	✓	✓			✓
Reduce cost to orbit	✓					✓
In-space transportation						✓

Tools and Test Techniques. To enhance testing techniques, tools will be developed, validated, and applied in the design of experimental flight vehicles. Objectives include developing fast, accurate, reliable prediction methods for complete aircraft design, developing design methods that contribute to a 50-percent reduction in the aircraft design time while increasing design confidence, and providing quick responses to requests from the civil aviation community for cooperative programs.

The Airframe Systems Concept to Test project focuses on the development of fast, accurate, and reliable analysis and design tools that significantly reduce aircraft development time and cost. Research efforts address barrier technologies in the areas of high-lift systems, including airframe noise, fuselage components, cruise wing configuration, and engine component flows, as they apply to increased design confidence and reduced development time.

The Methods for Affordable Design project will provide the tools to be used for system and trade studies in support of the conceptual development and preliminary design of advanced highly survivable aircraft. The goal is to provide validated next-generation design tools to increase design confidence and reduce the development cost and risk for high-performance aircraft, as well as to increase the survivability of high-performance aircraft concepts by one to two orders of magnitude. The objectives are to enable the routine use of validated computational fluid dynamics in early design and to develop and validate nonlinear flight dynamics (nonlinear, high alpha) design tools for high-performance aircraft.

All the Office of Aero-Space Technology Base R&T programs provide a national capability to respond quickly and effectively to critical issues identified by industry and other Government agencies for the public good. In addition, the Base R&T has supported cooperative programs in the exploration of new, emerging, high-risk, but potentially high-payoff, technologies. The Alternate Cooperative Capacity, Efficiency, and Safety Solutions project provides a method to quickly incorporate new cooperative research, related to civil transport aircraft, into the Airframe Systems program.

High-Performance Aircraft. This investment area is developing technology to reduce the design time for military aircraft and enhance aircraft operability and survivability. Objectives include developing advanced controls technologies that contribute to a 20-percent decrease in aircraft takeoff gross weight and a 30-percent increase in agility while enhancing survivability, supporting the development of new military air vehicle concepts and assist in solving technical problems with existing aircraft, developing and demonstrating airframe technologies for revolutionary military vehicle concepts that offer significant performance improvements, and developing technologies that improve total system survivability.

To improve range and/or payload, reduce cost, and improve survivability, the Aircraft Tactical Technology from Advanced Controls project is developing seamless control effector concepts that provide high levels of effectiveness with reduced weight, drag, complexity, and radar signature compared to state-of-the-art control effectors. Another objective is to develop real-time, integrated, nonlinear multi-element control law design methods that integrate, monitor, and use seamless control effectors to optimize performance for each mission segment.

NASA provides researchers and test engineers to work with the Department of Defense and industry counterparts on technical problems of mutual interest. Cooperative research projects with the

Defense Department have contributed to the development of high-payoff technologies such as vortex lift, multi-axis thrust vectoring, forebody controls, and high-angle-of-attack agility. Through the Advances through Cooperative Efforts project, NASA continues to strengthen this partnership with the Department of Defense. This project enables the application of NASA technical expertise and test facilities needed to support aircraft development on system upgrades, address in-service operation problems, and develop high-payoff technologies for military aircraft.

The Revolutionary Military Aircraft Technologies project is aimed at developing the high-payoff technologies and new fundamental understandings to enable revolutionary vehicle concepts to be designed and built. The project is exploring the full range of revolutionary technologies enabling these future vehicle concepts while reexamining the balance among performance, survivability, and costs. Emphasis will be placed on the air-mobility, bomber, patrol, and special-operations classes of aircraft.

Safety. The Airframe Systems program contributes to the Enterprise's safety goal by developing technologies in the areas of advanced flight decks, control systems, structural inspection methodologies, and enhanced crashworthiness of airframe structures. Objectives include developing technologies to protect against adverse consequences associated with errors in the flight deck and critical systems, achieving fail-safe, integrated control of the total aircraft through the advancement and integration of control theory, mathematical models, and formal methods, and developing the technologies that assure continued airworthiness of the aging commercial transport fleet and to enhance human survivability.

The goal of the Error-Proof Flight Deck and Aircraft Electronic Systems project is to develop technologies to protect against adverse affects associated with errors in the flight deck and mission-critical systems. Key objectives related to the flight deck include the development of revolutionary design methods and concepts, crew interfaces, and evaluation methods and tools for supporting flight decks that minimize operational errors and that are error tolerant. Flight-crucial mission systems objectives include the development of cost-effective design and assessment methods to protect against the electromagnetic corruption of digital components.

The goal of the Total Aircraft Management Environment project is to achieve totally integrated control of all airframe systems. This higher order control is sought to provide optimal performance and safety under all flight conditions. Such an environment must provide sensitivity to a maximum number of flight conditions and maximum adaptability to the dynamic environment. As more aircraft incorporate active control or some level of intelligent system implementation, the need for a total aircraft management environment in the future will become paramount. A key to the success of the project is to determine optimal and synergistic human-airframe relationships and interfaces.

The goal of Airframe Airworthiness Assurance is to develop technologies to ensure the continued airworthiness of the aging commercial transport fleet and to enhance human survivability in the event of an accident. Objectives include developing technologies to extend the useful safe life of aircraft systems, developing a systems approach to crashworthiness design, and assessing the needs and develop technology for fire prevention, detection, and suppression.

Breakthrough Technologies. The Airframe Systems program develops advanced breakthrough technologies that feed into the Enterprise's systems technology programs for further development

and risk reduction to help the U.S. aeronautics industry maintain its superiority in the global market. This is accomplished by developing revolutionary airframe concepts and technologies, techniques for efficiently producing aircraft, and technologies for enhancing aircraft efficiency. Objectives include developing key technologies to enable unconventional configurations, developing and validating integral metallic processing and design technologies for significant reduction in the manufacturing costs of fuselage structures, developing aircraft controller strategies for enhancing performance and reconfiguration capabilities, developing smart devices that use active component technologies to enable self-adaptive capability and pioneering long-term, high-risk fundamental technologies.

The Futuristic Airframe Concepts and Technologies project emphasizes the technologies required to allow subsonic commercial and cargo aircraft to benefit from unconventional configurations. The project addresses barrier technology in structures, materials, aerodynamics, airframe-propulsion integration, and acoustics to significantly expand design options for future subsonic transports. The technical approach involves developing and validating improved analyses and advanced technologies and concepts, integrated with ground and (potentially) flight experiments.

Today's airframe designs typically are riveted aluminum skin and stringer construction. Integral metallic structures promise significant cost reductions because of reductions in fastener count, detail part count, materials cost, joints, weight, and simplification of assembly. The Integral Airframe Structures project is developing the technologies required to demonstrate the feasibility of manufacturing large, integral, metallic structures for reducing the cost of manufacturing metal airframes. Key issues include the application and scaleup of advanced materials processes, analysis methodology development, demonstration of the durability and damage tolerance of integrally stiffened structures, and verification of cost assessment tools.

The objective of the Aircraft Morphing project is to develop smart devices with active components, such as dynamic actuation, local sensing, and feedback control, to increase aircraft efficiency and affordability. For many applications, these devices will modify local phenomena to support a macroscopic strategy, such as flow separation control for advanced, high-lift systems. In this multidisciplinary project, technologies are being developed to address advanced health monitoring, active structural damping, active noise reduction, and active separation control.

The Advanced Subsonic Transport Aircraft Research project includes the development of the intelligent adaptive control system that resides in the flight control system software to provide failure identification, propulsion controlled aircraft, reconfigurable control, and pilot awareness of flight-critical control system failure conditions. Under a cooperative effort with Boeing, the FAA, and the airlines, an intelligent adaptive control system for commercial transports is being developed and flight tested. In addition, "adaptive performance optimization" is an effort to develop and demonstrate a real-time, multisurface performance enhancing controller strategy for transport aircraft at cruise and climb conditions.

The objective of the Breakthrough Innovative Technologies project is to identify emerging technologies and concepts that could potentially have a large impact on airframe systems and to determine the viability of these technologies and concepts. The project is operated through NASA Research Announcements that define a broad set of technology areas in which university grants are awarded through a peer-reviewed process.

The goals of Revolutionary Airframe Noise and Emissions Reduction are to apply revolutionary airframe systems technologies to produce radical improvements in environmental compatibility through the significant reduction of noise and emissions. Technologies addressed will include airframe noise reduction (including that resulting from high-lift systems, landing gear cavities, and enclosures), propulsion airframe integration, concepts that address the noise emanating from flow impingement on pylons and engine components, and emissions reduction resulting from reduced fuel burn obtained by increased aerodynamic performance and innovative flight operations.

Systems Analysis. This investment area provides the systems analysis capability to conduct assessments of Enterprise programs and to conduct technology trade studies. The results will be used by Enterprise management and participating organizations to define systems-level impacts of technology and to help define effective investment strategies. Objectives include providing timely and credible systems-level analyses for determining investment strategies and technology impacts for senior managers in the Airframe Systems program and other Agency programs, developing the methodology, tools, and data bases required to conduct credible analyses, assessing the relative impact of all aeronautics program elements on the goals of the Three Pillars for Success, and supporting the planning teams for future new initiatives.

Propulsion Systems Program. The Propulsion Systems program focuses on the goals of maintaining U.S. superiority in engine development and ensuring the long-term environmental compatibility of propulsion systems. The program addresses critical propulsion technology needs across a broad range of vehicle classes. The objective is to develop and advance multidisciplinary propulsion technologies across the vehicle class investment areas (listed with their projects) in Table 9.3-5.

TABLE 9.3-5. PROPULSION SYSTEMS INVESTMENT AREAS

<i>General Aviation and Commuter</i>	<i>Subsonic Transport</i>	<i>High Speed Transports</i>	<i>High-Performance Aircraft</i>	<i>Hypersonic Vehicles</i>	<i>Crosscutting Research</i>
General Aviation Propulsion	ULTRASAFE	Fast, Quiet Engine	Affordable Propulsion for Survivability	Hybrid Hyperspeed Propulsion	Breakthrough Propulsion Technologies
	Smart Green Engine		Propulsion for Highly Survivable Vehicles		Experimental Methods
	High-Temperature Engine Materials and Structures				
	Physics and Process Modeling				

Table 9.3-6 shows the goals of the Aero-Space Technology / Enterprise supported by these investment areas.

TABLE 9.3-6. PROPULSION SYSTEMS SUPPORT OF ENTERPRISE GOALS

<i>Enterprise Goal</i>	<i>General Aviation Commuter</i>	<i>Subsonic Transports</i>	<i>High Speed Transports</i>	<i>High-performance Aircraft</i>	<i>Hypersonic Vehicles</i>	<i>Cross-cutting Research</i>
Reduce accident rate	✓	✓	✓			✓
Reduce emissions	✓	✓	✓			✓
Reduce noise levels	✓	✓	✓			✓
Reduce cost of air travel	✓	✓	✓			✓
Reduce travel time			✓			✓
Invigorate general aviation	✓					✓
Design tools/X-aircraft	✓	✓	✓	✓	✓	✓
Reduce cost to orbit					✓	✓
In-space transportation					✓	✓

General Aviation and Commuter. Little research and development has occurred in the area of general aviation during the severe market downturn of the past 20 years. New engines are a key factor to enable new airplane designs that can revitalize the light aircraft market. Demand and production will be stimulated by drastically reducing the costs of general aviation propulsion systems while improving their performance, ease of use, reliability, and environmental compatibility.

The goal of the General Aviation Propulsion (GAP) project is to develop, by 2000, affordable revolutionary propulsion systems for general aviation aircraft to revitalize the U.S. general aviation light aircraft industry. This effort will result in the development of technologies and manufacturing processes for affordable, environmentally compliant, revolutionary propulsion systems for general aviation aircraft, as well as in flight demonstrations of proof-of-concept propulsion systems in two propulsion system classes: turbine propulsion systems and intermittent combustion propulsion systems. The most promising concept in each class will be selected, designed, built, and flight demonstrated on existing or prototype airframes.

Subsonic Transports. Commercial transport propulsion systems will continue to be a critical source of revenue for the U.S. industry and a positive balance of trade for the U.S. economy. Projects have been structured around the technology needs required beyond the Advanced Subsonic Technology program.

The goal of the multidisciplinary High-Temperature Engine Materials and Structures project is to generate technologies for advanced materials, structural analysis codes, and high-temperature instrumentation that will enable the development of lightweight, affordable, long-term durability propulsion systems. Major consideration is being given to propulsion systems that will be friendly to the environment in terms of minimizing pollution and noise and that will be economical by

reducing fuel consumption per passenger mile, reducing direct operating costs, extending life, and improving reliability. High-temperature materials are the key to achieve these advances in propulsion systems. The project is focused on advanced alloys and lightweight composite materials to reduce component weight and to achieve advances in the operating temperature of engines compared to the current state of the art. Polymer matrix composites are being examined for potential uses in fans, compressors, casings, ducts, and engine control systems. Advanced alloys and metal matrix composites are under investigation for application in such areas as compressor and turbine disks, blades, and vanes. For extremely high-temperature applications, ceramic matrix composites are being explored. Initial applications may include turbine vanes and ultimately turbine blades and disks, or blisks.

The objectives of the **Physics and Process Modeling** project are to validate design and processing technologies that contribute to reductions in development time and cost and to validate selected concepts to reduce further development risk. The technical approach is a combined experimental and analytical research program aimed at validated tools, analyses, data, concepts, and capabilities. The effort can be represented by three categories: physics-based modeling, process modeling, and concept validation. Physics-based modeling of materials and components identifies fundamental understanding and supports analytical simulation techniques that enable lower cost and/or time of turbomachinery subsystems development. Physics-based modeling of processing is focused on integrated design and manufacturing tools that enable faster, less expensive development cycles and on technology that enables lower cost manufacturing methods. Key characteristics of advanced concepts are being validated to make them affordable by reducing the risk of their development.

The goal of **ULTRASAFE** (Engine Failure Containment) is to reduce engine component failure to an absolute minimum and to contain all possible fragments if an occasional failure does occur. The project consists of two technical elements: engine containment and crack-resistant materials. In the area of crack-resistant materials, the goal is to develop long-life, durable engine/component materials to double resistance to failure. Emphasis is directed at engine containment to develop enhanced, lightweight material systems.

The principal aim of the **Smart Green Engine** project is to develop enabling technologies that will minimize all environmentally harmful engine emissions. By seeking to further reduce nitrogen oxide emissions beyond Advanced Subsonic Technology program goals, as well as addressing particulates and aerosols, this project leads into the next environmental focused program. The impact of carbon dioxide on the environment requires this project to also consider methods for reducing the fuel burn. This project is demonstrating the benefits of smart operability of turbomachinery and engine systems and exploring and demonstrating low-fuel-burn, low-emissions techniques. Some specific technologies being pursued include active and passive compressor stall management, magnetic bearing suspension, highly loaded turbomachinery, coolant flow management, active combustion controls, computational fluid dynamics tools and models, and wave rotor technology for topping cycles.

High Speed Transports. The High Speed Research program has a goal of developing technologies that will enable a High Speed Civil Transport (HSCT) to be produced with a ticket price that has a 20-percent premium over subsonic commercial transports. To develop an even more cost-

competitive HSCT, this investment area is focused on developing propulsion technology to provide the breakthroughs in emission and noise technologies necessary to approach near-zero levels of environmental impact.

The goal of the Fast, Quiet Engine project is to develop and demonstrate, by 2005, propulsion technologies that will enable the design of high-performance, long-life, lightweight, low-emission, and low-noise engines for future generations of supersonic aircraft. The research, both computational and experimental, is aimed at evaluating and analyzing promising technologies that offer significant reductions in noise and emissions for next-generation supersonic propulsion systems for commercial aircraft. Better fundamental understanding of the flow physics in inlets, nozzles, turbomachinery, and combustors will enable the development of innovative low-noise and low-emissions concepts. The approach is to develop and experimentally validate advanced analytical tools in conjunction with fundamental and applied experiments.

High-Performance Aircraft. Propulsion technologies to simultaneously attain performance, affordability, and survivability goals are the products of this investment area. Two highly integrated projects are structured to address this problem up to the level of large-scale technology validation. The cost of incorporating survivability into advanced aircraft is strongly influenced by the design of the propulsion system.

The goal of the Affordable Propulsion for Survivability project is to develop materials, coatings, and subsystems that display conventional levels of durability while reducing signatures. The overall objective is to validate signature reduction and prediction methods to achieve more efficient design processes. The project objectives are strongly integrated with related efforts in the Airframe Systems and Flight Research programs.

The goal of the Propulsion for Highly Survivable Vehicles project is to design, fabricate, and experimentally evaluate propulsion system components capable of meeting the signature requirements of highly survivable vehicles. Technology advances in this project will lead the way for the design of new experimental aircraft.

Hypersonic Vehicles. Air-breathing hypersonic flight is being examined for application in access to space. Bringing airplane-like operations to the space launch infrastructure requires robust systems.

The objective of the Hybrid Hyperspeed Propulsion project is to establish a low-risk technical benchmark for air-breathing launch vehicle performance. The objective is to be accomplished by quickly obtaining "hard" data on the benefits promised by rocket-based combined-cycle, or ejector-ramjet, propulsion systems. This project will undertake the ground demonstration of fundamental component and system technologies for a rocket-based combined-cycle integrated propulsion system.

Crosscutting Research. The goal of Breakthrough Propulsion Technologies is to support cross-cutting fundamental and innovative research in propulsion-related disciplines in partnership with the U.S. academic research community. The Breakthrough Propulsion Technologies project crosses all propulsion-related disciplines, including fluids, structures, instrumentation and controls, and multidisciplinary design and analysis.

The goal of Experimental Methods is to provide adequate maintenance to ensure facility reliability while increasing data quality and productivity for research testing at the aeropropulsion test facilities. Experimental Methods is responsible for the maintenance, product assurance, safety, and enhancements across all aeropropulsion facilities to provide support for current and planned propulsion research programs.

Flight Research Program. The objective of the Flight Research program is to develop and demonstrate advanced technology concepts and methodologies, provide advanced validated tools and techniques, respond quickly to critical national issues, and provide the basis on which future focused programs are built. The following details the investment areas that are included in the Flight Research program are listed in Table 9.3-7.

<i>High Altitude, Long Endurance Sensing</i>	<i>Advanced System Concepts</i>	<i>Highly Maneuverable Aircraft</i>	<i>Flight Research Productivity</i>
Environmental Research Aircraft and Sensor Technology	Advanced Flight Concepts Advanced Controls Revolutionary Concepts Flight Research	Integrated Controls	Test Tools and Test Methods Flight Systems Research Center Flight Testbeds Safety Technology Insertion

TABLE 9.3-7. FLIGHT RESEARCH INVESTMENT AREAS

Table 9.3-8 shows the goals of the Aero-Space Technology Enterprise supported by the Flight Research investment areas.

<i>Enterprise Goal</i>	<i>High Altitude, Long Endurance Sensing</i>	<i>Advanced Systems Concepts</i>	<i>Highly Maneuverable Aircraft</i>	<i>Flight Research Productivity</i>
Reduce accident rate				✓
Reduce emissions	✓			
Reduce cost of air travel		✓		
Design tools/X-planes	✓	✓	✓	✓

TABLE 9.3-8. FLIGHT RESEARCH SUPPORT OF ENTERPRISE GOALS

High Altitude, Long Endurance Sensing. This investment area supports the industry Remotely Piloted Airplane (RPA) technology development as well as sensor integration for RPA

performance demonstration missions and scientific dropsonde demonstrations above 55,000 feet. The objectives include supporting the development of RPA technologies in support of very high-altitude, high-altitude, long-endurance, and extreme-duration missions, developing automation approaches for airborne sensors in science RPA, and transferring technology to U.S. industry to establish competitive capability.

Environmental Research Airplanes and Sensor Technology (ERAST) is providing technology that will enable practical flight operations of uninhabited aircraft by customers such as the Earth Science Enterprise. It will also increase the performance capabilities of uninhabited vehicles beyond the current atmospheric sensing platforms, reaching higher altitudes and achieving missions of longer duration and providing atmospheric scientific data in regions unattainable with previous technology. ERAST Missions Maturation is intended as part of a joint partnership with the Earth Science Enterprise. The objective is to further operational maturation of RPA science platforms, with improved reliability and utility for the science community.

Advanced Systems Concepts. The emphasis of this investment area is innovative use of advanced electronic, optical, and mechanical systems to meet the following objectives: demonstrate smart aircraft designed for reduced cost of ownership through in-flight concept demonstrations, obtain hypersonic flight measurements of fundamental internal and external flow phenomenon, gain substantial improvements in performance by developing offboard air/vehicle command and piloting concepts, and validate revolutionary concepts involving unique configurations in flight.

The Advanced Flight Concepts project includes a range of exploratory and/or nontraditional applications. This ranges from hypersonics baseline experiments to unconventional systems concepts. In the area of hypersonics, the Physics Hypersonic flight experiment will provide cross-flow boundary layer flight data at Mach 8 just prior to the Pegasus first-stage engine cutoff. The Axisymmetric Scramjet experiment will provide Mach 6.5 flight data from a Russia-based ground launch in a joint flight experiment with the Central Institute of Aviation Motors. In the area of unconventional systems, the Autonomous Formation Flight experiment will demonstrate the practicality of doubling the performance capability of systems of aerial platforms having five or more members through the use of innovative remotely piloted and autonomous aircraft technologies. The Control of Autonomous/Human Multiplatform Systems experiment will demonstrate multiplatform flight operations, with a mix of uninhabited and piloted air vehicles, as well as a mix of autonomous and human-operated aircraft.

The Advanced Controls project develops new controls technology to reduce vehicle acquisition and operational costs. The Active Aeroelastic Wing experiment will demonstrate aircraft roll control through the twisting of the wing box, resulting in reduced aircraft weight and wing strength requirements and lower operating costs. These are accomplished by tailoring wing twist to flight conditions, resulting in minimal control surface movement and leading to reduced aerodynamic drag and improved fuel efficiency. The Advanced Vehicle Systems task integrates electric aircraft subsystems, emerging vehicle management systems, fiber optic communication systems, and advanced vehicle control applications in a distributed architecture for primary flight control and vehicle management. In partnership with the Department of Defense, the More-electric Technology Validation will flight validate electric technologies such as a fault-tolerant solid-state 270 volts direct current electrical power generation and management system. The Reconfigurable Systems for Tailless Fighter Aircraft task is to develop reconfigurable control law design methods

and algorithms and apply them to advanced low-signature (tailless) fighter aircraft configurations. Revolutionary Concepts Flight Research will be carried out in cooperation with the Airframe Systems program. It is designed to accelerate the identification of technology applications and vehicle concepts that offer revolutionary capabilities to meet and exceed the stretch goals of the Enterprise's Strategic Plan.

Highly Maneuverable Aircraft. The principal focus is on integrated propulsion and flight controls to achieve dramatic improvement in maneuverability performance of operational aircraft and maturing survivability technology for highly maneuverable aircraft.

The Integrated Controls project emphasizes the integration of propulsion exhaust vectoring with the airframe flight controls to achieve dramatic improvements in total system performance. The Advanced Controls Technology for Integrated Vehicles Experiment (ACTIVE) integrates technology development in two other Base R&T programs: the inlet distortion-tolerant control system design effort in Propulsion Systems and the Intelligent Controls effort in Information Technology. The Vectoring, Extremely Short Takeoff and Landing, Control and Tailless Operation Research will extend the results of ACTIVE to the terminal area, particularly for aircraft carrier operations, and combines vectored thrust with integrated flight controls.

Flight Research Productivity. This investment area provides flight data to enable the validation of design tools and techniques, the application of aviation safety technology through technology insertion, and better performing flight research tools and test techniques for a range of flight regimes. The objectives include evaluating operational characteristics of full-scale supersonic transport aircraft to include aerodynamics, aerothermodynamics, handling qualities, structures, and cabin noise, applying significant advances in flight-flow-visualization methods, improved sensors, and quantitative test techniques for more accurate measurements of engine and airframe flow characteristics, and identifying the flight research necessary to mature aviation safety technology and transfer it to the manufacturers and air carriers.

New or enabling flight Test Tools and Test Methods are developed at the concept or prototype level to increase the efficiency and quality of flight test data that can be obtained. These tools or methods are applied to new or ongoing flight projects. This area also includes disciplinary flight research, in which conceptual ideas are investigated prior to committing to a more sizable flight project.

The Flight Systems Research Center at the University of California at Los Angeles (UCLA) brings together academia and flight research practitioners to pursue research studies for a wide variety of technical disciplines. Such work will provide a practical orientation to new flight systems concepts.

Flight research, and in many situations experimental data, can be obtained through use of Flight Testbeds at a lower cost and with more credible results than with other forms of experimental approach. The testbeds span a wide range of conditions, from heavy lift (B-52) to very high speed (SR-71).

Safety Technology Insertion will accelerate the maturity of weather-related accident prevention technologies required for the in-flight detection of hazardous atmospheric conditions, such as clear air turbulence, wake vortices, and wind shear. Enhancements to existing Light Intersection

Detection and Ranging (LIDAR) scanning technologies include implementation of the technology internal to the aircraft's structural envelope and also validate new designs to increase scanning planes from one to two dimensions. The C-17 Research Flight Control System will be used to facilitate flight research in other areas of NASA's Aviation Safety program, such as control of aircraft in adverse conditions, flight-critical systems, health monitoring, design and integration, and turbulence. This flight research tool allows for the rapid validation of control designs for transport configurations.

Aviation Operations Systems Program. Aviation operations systems are defined as those ground, satellite, and aircraft systems and human operators that determine the operational safety, efficiency, and capacity of aircraft operating in the airspace. It specifically encompasses communication, navigation, and surveillance systems; air traffic management systems, interfaces, and procedures; relevant cockpit systems, interfaces, and procedures; operational human factors, their impact on aviation operations, and error mitigation; and weather and hazardous environment characterization, detection, and avoidance systems. The products of the Aviation Operations Systems program are advanced systems concepts, operational procedures and countermeasures, models, and data. The program investment areas and their projects are listed in Table 9.3-9.

TABLE 9.3-9. AVIATION OPERATION SYSTEMS INVESTMENT AREAS

<i>System Design, Assessment, and Reliability</i>	<i>Human Performance and Countermeasures</i>	<i>Hazardous Environment Prediction and Mitigation</i>
Human-Automation Integration Research	Maintenance Operations and Training	Aircraft Icing
Methods for Analysis of System Stability and Safety	Psychological-Physiological Stressors and Factors	Aviation Weather Information
Cost-Benefit Operational Safety Testing Models		

Table 9.3-10 shows the goals of the Aero-Space Technology Enterprise supported by the Aviation Operations Systems program's investment areas.

TABLE 9.3-10. AVIATION OPERATIONS SYSTEMS SUPPORT OF ENTERPRISE GOALS

<i>Enterprise Goal</i>	<i>System Design, Assessment, and Reliability</i>	<i>Human Performance and Countermeasures</i>	<i>Hazardous Environment Prediction and Mitigation</i>
Reduce accident rate	✓	✓	✓

System Design, Assessment, and Reliability. The aviation system is a complex integration of humans and automated systems. The interaction of humans with these complex systems, both in their operation and their development, is a contributing factor in many accidents and incidents.

The Human-Automation Integration Research project develops validated tools and prototyping testbeds for the design and analysis of innovative human-automation systems in air, ground, and integrated airspace operations. The goals are to improve communication and collaboration among system designers and human factors experts, to identify and eliminate or mitigate risk factors during the design phase for automation-related operator error, and to improve operator understanding of automated systems.

The Methods for Analysis of System Stability and Safety project focuses on two coordinated development efforts: safety data analysis and systemwide monitoring, modeling, and simulation. The safety data analysis element supports the development of enabling technologies to facilitate analyses of data collected by the various components and shareholders of the airspace system. The systemwide monitoring, modeling, and simulation element supports the development of methods to monitor the performance and health of the airspace system and to predict the systemwide effects of changes through modeling and simulation.

The Cost-benefit Operational Safety Testing Models project develops models for simulating and analyzing system performance, including the contributions of individual operators, individual elements of systems (ramp, tower, transition airspace, and en route elements), and large-scale system flow and control issues. It will be a vertically integrated model development activity, based around a core representation of the fundamental processes of air traffic management, models of dynamically driven aircraft, models of weather and airspace, and models (essentially rule-based) that represent the "knowledge" of air traffic management.

Human Performance and Countermeasures. Human error is cited as a contributing factor in the majority of all aviation accidents and incidents. The objective of this investment area is to develop knowledge bases and models of fundamental human information processing capabilities and to use them in the development of technologies to enhance them or countermeasures to mitigate them.

The Maintenance Operations and Training Research project develops procedures and technologies to clarify the roles and responsibilities of aircraft maintenance teams and training techniques that instill the skills required to respond quickly and appropriately to flight-critical situations. The Maintenance Operations task addresses human error in aerospace maintenance by developing interventions and technologies to enhance safety and effectiveness of maintenance operations through improved teamwork, communications, and procedures and displays. The Training task addresses technologies to reduce crew errors in procedures, decisionmaking, situation awareness, automation use, and weather planning so pilots and flight and ground teams can function quickly and efficiently in routine and abnormal operations.

The Psychological-Physiological Stressors and Factors project develops new technologies and procedures to measure and reduce increased stress in human operators within the airspace system. Human perception research focuses on the development of new methods, computational models, and metrics that will enable optimization of operator sensory-motor interaction with the displays

and controls of the National Airspace System. Human cognitive research will focus on developing models of the human operator information processing during interaction with the air transportation system, with the goal of understanding how operator attention may be focused on or by the system.

Hazardous Environment Prediction and Mitigation. Environmental hazards are major contributing factors to aviation accidents and incidents. Databases, knowledge bases, models, and predictive technologies are required to assess critical weather influences on both safety and efficiency.

The Aircraft Icing project develops validated analytical and experimental tools to support design and certification or qualification of aircraft systems in icing, to understand the effects of ice contamination on aircraft performance, stability and control, and handling qualities, and to foster the development of ice protection systems, including ice sensing, prevention and removal, and avoidance. This requires a balance among analytical and computational simulations, experimental research, and flight research.

The Aviation Weather Information project develops the technology required to eliminate atmospheric hazards as a safety concern for aircraft operations in all weather conditions. The project focuses on sensor and real-time communications technology development and the integration into a usable system for aiding pilots, air traffic controllers, and air transport dispatch personnel in improving the safety and efficiency of aircraft operations.

Rotorcraft. The goals of the Rotorcraft program are to provide technology leadership to ensure economic competitiveness and technology superiority of the U.S. rotorcraft industry, to develop technology to maintain military supremacy of U.S. military rotorcraft through a partnership with the Department of Defense, and to develop technology to ensure safety and environmental compatibility of civil rotorcraft through a partnership with the FAA. The rotorcraft program meets the challenge for technology leadership through both short- and long-term focuses. The short-term goals are accomplished via the National Rotorcraft Technology Center. The long-term goals are strongly coupled with both industry and academia through the Enterprise strategic planning process and direct customer interaction. The Rotorcraft program has four investment areas aligned one for one with the projects of the program. Table 9.3-11 shows the goals of the Aero-Space Technology Enterprise supported by the Rotorcraft investment areas.

TABLE 9.3-11. ROTORCRAFT SUPPORT OF ENTERPRISE GOALS

<i>Enterprise Goal</i>	<i>Design for Efficient and Affordable Rotorcraft</i>	<i>Select Integrated Low-Noise Technologies</i>	<i>Safe All-Weather Operations for Rotorcraft</i>	<i>Fast Response Industry Assistance Requests</i>
Reduce accident rate			✓	✓
Reduce noise levels		✓		✓
Triple throughput				✓
Reduce cost of air travel	✓			✓
Design tools/X-aircraft	✓			✓

Design for Efficient and Affordable Rotorcraft (DEAR). Senior executives of the U.S. Government and industry have identified affordability as the most significant of several barrier issues affecting the worldwide competitiveness of rotorcraft and a potential limit to their broader use. The current worldwide fleet of 25,000 rotorcraft represents a very large replacement market because many of these aircraft are 30 to 40 years old. The primary drawback to these replacements and new growth is cost. DEAR addresses three technical areas that have a major impact on both development time and cost. The first is the development, validation, and insertion into the industry design cycle of aeromechanics computational models and design tools. The second is the development of rotor design concepts that significantly increase performance and efficiency while reducing vibration loads. The third area is the development of tools and design concepts for the implementation of low-cost, reliable, and efficient composite structures in the rotorcraft design process.

Select Integrated Low-Noise Technologies. Rotorcraft are important segments of the Nation's transportation system, and they are poised for slow but steady growth throughout the coming years. FAA and aviation industry experts project that the demand for short-haul air service, such as intercity travel and air tour operations, will increase. Although overall community noise levels (caused by all types of aircraft) may temporarily decrease with the phaseout of Stage II turbojet airplanes, the noise impact of rotorcraft is expected to increase because of increased operations. The Select Integrated Low-Noise Technologies project encompasses three areas for reduced noise. First, efforts are devoted to the powertrain to reduce transmission noise and vibration entering the interior environment of the aircraft's cabin. Second, research on effective noise and vibration reduction technologies for the rotor system addresses a portfolio of technologies, including both low- and high-risk concepts, both emerging and maturing technologies, and the ability to design and predict the behavior of these advanced concepts. Third, a dedicated effort is being undertaken to develop and assess specialized flight operations that minimize noise impact, do not require any retrofitting of equipment or technology onto the aircraft, and thus are a very low-cost approach to noise reduction.

Safe All-Weather Flight Operations for Rotorcraft. Intensified public and regulatory demands for greater safety in air travel present a major challenge for the rotorcraft community. Not only do the inherent vehicle design and reliability issues differ significantly for rotorcraft, but their unique capabilities result in exposure to a significantly different, arguably more risk-prone, operational environment. This effort is divided into two major technology development thrusts: Human-Centered Cockpit Technology and Rotorcraft Drive System Technology. The Human-Centered Cockpit Technology thrust focuses on technologies in flight control and guidance and situation awareness and information display for rotorcraft accident prevention, mitigation, and direct intervention. Rotorcraft Drive System Technology includes validated methods for health and condition monitors for transmissions and gearboxes, gear crack growth models, life models, design rules for ultrasafe gears, data bases on advanced materials and lubricants, and advanced designs of gears and bearings.

Fast Response Industry Assistance for Rotorcraft (FRIAR). This project responds to the near-term technology development needs of the U.S. rotorcraft community and enables the other projects of the Rotorcraft program to focus more on the longer term high-risk objectives. The primary component of FRIAR is the National Rotorcraft Technology Center (NRTC), a unique

Government-industry-academic partnership. NASA, the Army, the Navy, and the FAA are the Government participants in the NRTC. Bell Helicopter Textron, Boeing Space and Defense Group, and Sikorsky Aircraft are industry's principal members of the Rotorcraft Industry Technology Association, a corporation and focal point formed for this purpose. The NRTC is cofunded on the Government side by NASA and the Department of Defense to develop technology to ensure the economic competitiveness and continued military supremacy of U.S. rotorcraft. The rotorcraft industry matches the Government investment, on a dollar-for-dollar basis, and shares equally in all resulting technology developed within the program. An annual research portfolio of technology projects is proposed (and cofunded) by the industry members, refined with participation by Government technical specialists, and evaluated and approved by the Government. The projects must be responsive to NASA and Defense Department goals, and emphasis is on technologies for affordability, safety, passenger/community acceptance, and enhanced operations and aviation throughput. The projects are relatively near term (2.5-year average duration), involve a high degree of teaming among participating manufacturers, use subcontract manufacturer, academic, and Government laboratory capabilities as appropriate, and typically include validation. Other important characteristics include aggressive technology transfer among members, early technology insertion, and, in many cases, U.S. rotorcraft industry consensus on design philosophies and standards. There are currently two other efforts under the FRIAR project in addition to the NRTC: an effort in support of the National Transportation Safety Board and short takeoff vertical landing technology work undertaken as a cooperative effort with the U.S. Navy.

Aeronautics Systems Technology Programs

High Performance Computing and Communications Program. The main objective of the Federal HPCC program is to extend U.S. technological leadership in high-performance computing and computer communications. As this is accomplished, these technologies will be widely disseminated to accelerate the pace of innovation and improve national economic competitiveness, national security, education, health care, and the global environment. The NASA HPCC program is a critical element of the Federal HPCC program. Since its inception, the Federal HPCC program has focused on research and development in a wide range of high-performance computing and communications technologies grouped into five areas: High End Computing and Computation (HECC), Large Scale Networking, High Confidence Systems, Human Centered Systems, and Education, Training, and Human Resources. The NASA program makes significant contribution to all five areas, but the majority of funding is directed to HECC.

NASA's specific goals are to (1) accelerate the development, application, and transfer of high-performance computing and computer communications technologies to meet the engineering and science needs of the U.S. aerospace, Earth and space science, spaceborne research, and education communities and (2) accelerate the distribution of technologies to the American public. NASA's primary contribution to the Federal program is its leadership in the development of applications software and algorithms for massively parallel computing systems, which will increase system performance to the sustained TeraFLOPS (10^{12} floating point operations per second) level for NASA applications.

As HPCC technologies are developed, NASA will use them to solve its "Grand Challenge" research problems. These are fundamental problems whose solutions require significant increases

in computational power and are critical to meeting national needs. The science and engineering requirements inherent in these applications require at least three orders-of-magnitude improvement in high-performance computing and networking capabilities over the capabilities that existed in 1992. The NASA HPCC program is developing and demonstrating high-performance architectures, algorithms, software tools, and operating systems using prototypes and developmental testbed systems. These testbed systems will be scaleable to TeraFLOPS computational and terabits-per-second communications performance levels.

NASA's "Grand Challenges" include improving the design and simulation of advanced aerospace vehicles, enabling people at remote locations to communicate more effectively and share information, increasing scientists' abilities to model Earth's climate and forecast global environmental trends, and improving the capabilities of advanced spacecraft to explore Earth and the solar system. An additional component of NASA's HPCC program further broadens the reach of the program by supporting research and development in education, digital library technology, and access to Earth and space science data. Underlying and supporting all NASA HPCC program components is an element of basic research, development, and application of networking technology, which contributes also to providing new capabilities for the Next Generation Internet (NGI).

Computational AeroSciences. The Computational AeroSciences project was originally oriented around the longer term thrust of exploration of future high-end supercomputing for aerospace needs—extreme high-performance computing. As a result of interactions with industry, Computational AeroSciences has added research efforts toward the use of networked workstations in the design environment. The short-term thrust is to make effective use of current-generation computing hardware to reduce costs. The long-term payoff is developing an understanding of the system software and networking technologies required to link a very large number of shared heterogeneous processors together. This understanding will be required to achieve computational speeds far beyond TeraFLOPS.

Earth and Space Sciences. The Earth and Space Sciences project demonstrates TeraFLOPS systems performance to further our understanding and ability to predict the dynamic interaction of physical, chemical, and biological processes affecting Earth, the solar-terrestrial environment, and the universe. This means a new understanding of the formations, distances, and revolutions of the celestial bodies, protecting world satellites from solar activity and heliospheric dynamics and predicting climate change. The computing techniques realized are furthering the development of a suite of multidisciplinary models, leading ultimately to scaleable global climate simulations and to highly energetic multiple-scale problems associated with astrophysics.

Remote Exploration and Experimentation. The Remote Exploration and Experimentation project will develop low-power, fault-tolerant, high-performance, scaleable computing technology for a new generation of microspacecraft. This technology will embrace architectures scaleable from subwatt systems to hundred-watt systems that support a wide range of missions and from Earth-observing missions to deep space missions lasting 10 years or more. Earth-observing missions are typically conducted in a data-rich/power-rich environment with sensors capable of producing gigabits to terabits per second. Deep space missions require ultralow-power and low-mass systems capable of autonomous control of complex robotic functions. These space-based systems must be highly reliable and fault tolerant under extreme radiation conditions.

Learning Technologies. The Learning Technologies project consists of four elements that seek to accelerate the innovative distribution of technologies to the American educational community through NASA science, engineering, and technology contributions. The Digital Library element fosters the development of new and innovative technology to support digital libraries in the classroom with pilot projects designed for eventual scaleup to millions of users widely distributed over the Internet. The Special Projects element uses remote-sensing data to provide kindergarten through 12th grade (K-12) access to NASA data bases of remote-sensing images and data over computer networks, such as the Internet. The K-12 Educational Outreach element focuses on developing curriculum enhancement products for a broad cross-section of the educational community over the Internet, building on a core of education programs at NASA Centers, and expanding a broad outreach program to educational product developers in academia and the private sector. The K-12 Aeronautics element focuses on developing students in the fields of aeronautics at an early age to bring new creative talent into the industry.

NASA Research and Education Network. The NASA Research and Education Network (NREN) project carries out computer network research that supports the other four projects. NREN provides a network testbed that balances NASA's HPCC community requirements for networking research and research networking. It is used to perform research into promising, high-risk, high-performance network technology and will establish standards and provide working models for commercial communications and networking infrastructure deployment. NREN's role is to deploy the advanced communications required by "Grand Challenge" investigators in a manner that satisfies the immediate needs of the researcher while simultaneously guiding commercial infrastructure development for the Nation. NREN also supports the Federal Large Scale Networking NGI Initiative. The objective of the NGI is to assure U.S. technological leadership in communications through research and development that advances the leading edge of networking technologies and services. The NGI is a multi-agency development and deployment effort designed to provide network connectivity at significantly higher performance, enabling next-generation networking applications among scientists, engineers, and computing resources of the Federal HPCC program.

High Speed Research Program. The projected 15-year market for the HSCT is more than 500 aircraft, resulting in approximately \$200 billion in aircraft sales for the U.S. aerospace industry and 140,000 high-quality jobs. The goal of NASA's High Speed Research (HSR) program is to help ensure U.S. industry's continued preeminence in aeronautics well into the next century by developing technology that will enable an environmentally compatible and economically viable HSCT aircraft. The HSR program is being conducted in two phases. Phase I, initiated in FY 1990 and concluded in September 1996, defined critical HSCT environmental compatibility requirements in the areas of atmospheric effects, community noise, and sonic boom and established a technology foundation to meet these requirements. Phase II of the HSR program was initiated in FY 1993 and addresses a recognized Government role in conducting long-lead, high-risk research and technology development and validation.

HSR Phase I. The possibility that HSCT engine emissions might cause depletion of stratospheric ozone was specifically addressed through the development of improved atmospheric models and their application in assessing the effects of a large fleet of aircraft under realistic operating scenarios. These activities involved direct participation of internationally renowned scientists and

regulatory officials to provide a technical basis that is as strong as possible for establishing suitable standards. In related efforts, research on advanced combustor concepts was conducted with the goal of achieving a nitrogen oxide emissions index of no greater than 5 grams per kilogram fuel burned—an order-of-magnitude improvement relative to using today's technology. Public acceptance of the HSCT also depends on its ability to achieve noise levels compatible with the coexisting subsonic fleet. A program goal has been set to achieve noise levels lower than the limits of Federal Aviation Regulation 36, Stage 3, noise levels now applied to newly designed subsonic transports. Low-boom research resulted in configurations that had lower boom but were not economically viable. Because HSCT market projections were only based on supersonic flight over water and not low-boom configurations, subsequent sonic boom research was directed toward understanding sonic boom effects on marine animals and avoidance of human and animal exposure. Phase I provided the confidence that the necessary technology can be developed to satisfy the critical concerns.

HSR Phase II. The propulsion and airframe projects are highly focused on developing major new capabilities. The propulsion project emphasizes selected individual subscale component and materials technology development efforts required for subsequent industry design of an HSCT engine. The technical challenge is developing a propulsion system that would be environmentally compatible in terms of meeting low emissions and noise requirements and economically viable in terms of performance and durability. Key specific goals for the propulsion project are:

- Low-emissions combustor (with emissions no greater than 5 grams of NO_x per kilogram fuel) demonstration
- Low-noise, lightweight, and highly efficient exhaust nozzle (with a 15–20-decibel noise suppression and a cruise thrust coefficient of 0.98 at supersonic cruise) demonstration
- Durable combustor liner materials with temperature capabilities up to 2,200 degrees Fahrenheit with no film cooling
- Durable nozzle materials with temperature capabilities up to 1,880 degree Fahrenheit
- Mixed-compression inlet system for high-performance and low approach noise with stable operation

The final propulsion project deliverables are full-scale engine and nozzle technology demonstrator tests with supporting materials applications efforts for the engine materials.

The airframe project emphasizes technology development efforts in aerodynamics, materials and structures, and flight deck systems required for subsequent industry design of a viable HSCT airframe. Key specific goals for the airframe project are:

- Advanced aerodynamics that provide a 33-percent increase in aircraft range and a 50-percent reduction in the takeoff noise footprint using current technology
- Wing and fuselage materials and structural concepts that are 33 percent lighter than can be achieved using current technology and a durability to survive flight temperatures up to 350 degrees Fahrenheit for 60,000 hours
- Advanced cockpit concepts incorporating synthetic vision, high-level information management, and integrated displays and controls for safe and efficient aircraft operations in the international airspace system.

The final airframe project deliverables are full-scale airframe fabrication and tests of fuselage and wingbox subassemblies fabricated with optimized preproduction processes using mission-capable materials for structural weight and cost validation.

Advanced Subsonic Technology Program. NASA's role in civil aeronautics is to develop technology to a level of readiness appropriate to ensure that U.S. industry is prepared to meet the anticipated demands on the aviation system. These demands include growing air traffic volume (which is predicted to triple in 20 years), more stringent requirements issued through FAA inspection directives to preserve air travel safety and decreased accident rates, increasingly strict international regulations in response to environmental concerns (such as noise and emissions), and the demand for industry and airlines to produce and operate a cost-effective aircraft fleet. NASA provides the leadership in new technology development and ensures its readiness for transfer to industry and the FAA, the ultimate users who have primary responsibility for the application of candidate technologies, including operational demonstration and systems engineering. The objective of NASA's Advanced Subsonic Technology (AST) program is to provide high-risk, high-payoff technologies for safe travel in the global air transportation system, for environmentally compatible aircraft, and for reduced seat cost.

The AST program is fostering the development of key emerging technologies that offer high-leverage payoffs by placing special emphasis in the areas key to aeronautics leadership: safety, environment, capacity, reduced seat cost, and general aviation. These key areas and their projects are listed in Table 9.3-12.

TABLE 9.3-12. ADVANCED SUBSONIC TECHNOLOGY INVESTMENT AREAS

<i>Safety</i>	<i>Environment</i>	<i>Aviation Systems Capacity</i>	<i>Reduced Seat Cost</i>	<i>General Aviation</i>
Aging Aircraft	Noise Reduction Emissions Reduction Environmental Assessment	Terminal Area Productivity Advanced Air Transportation Technology Civil Tiltrotor	Engine Systems Airframe Materials and Structures Airframe Methods and Design Environment Integration Systems Evaluation	AGATE

The integration of the critical elements of the AST program provides a focused technology foundation to ensure that U.S. commercial transports and general aviation aircraft continue to provide safe transportation, significantly decrease the impact on the environment, increase aviation system throughput, and decrease the cost of air travel. Table 9.3-13 shows the goals of the Enterprise supported by the AST investment areas.

TABLE 9.3-13. ADVANCED SUBSONIC TECHNOLOGY SUPPORT OF ENTERPRISE GOALS

<i>Enterprise Goal</i>	<i>Safety</i>	<i>Environment</i>	<i>Aviation Systems Capacity</i>	<i>Reduced Seat Cost</i>	<i>General Aviation</i>
Reduce accident rate	✓			✓	
Reduce emissions		✓		✓	
Reduce noise levels		✓		✓	
Triple throughput				✓	
Reduce cost of air travel			✓	✓	
Invigorate general aviation					✓

Safety. In 1990, approximately 46 percent of the U.S. commercial air transport fleet was more than 15 years old, and 26 percent was more than 20 years old. The number of aircraft over 20 years old will double by the year 2000. Technology advances in automated inspection of airframes and validated structural life prediction are essential to economically maintain the safe operation of this fleet.

Initiated in response to structural failures in the aging U.S. commercial aircraft fleet, the Aging Aircraft project builds on NASA's extensive research base in nondestructive evaluation methods, metal fatigue, and modeling for structural life prediction. The prediction methodology necessary to calculate the residual strength in commercial aircraft airframes and the advanced nondestructive evaluation technology that replaces costly and subjective techniques to reliably detect disbonds, fatigue cracks, and corrosion will provide the industry with the tools to affordably address the aging aircraft structural safety concerns.

Environment. It is inevitable that more stringent and more encompassing international environmental standards will be established to reduce aircraft noise and engine emissions, particularly in airport takeoff and landing operations. In addition to mandates by the U.S. Congress, the European Community and the International Civil Aviation Organization (ICAO) have taken action in response to these concerns. These environmental issues will and continue to inhibit aircraft operations, unless advances in both noise and emission reduction technologies are realized.

In cooperation with U.S. industry and the FAA, the Noise Reduction project targets technologies to reduce aircraft noise levels by 10 decibels, relative to the 1992 production technology, by the year 2000 for future subsonic transports. Early in the project history, an industry-led effort specifically defined 1992 production technology for four classes of subsonic transport airplanes as the baseline for measuring the effect of noise reduction technology. Technologies that meet these goals will provide the design margins for the next generation of subsonic transport aircraft and engines.

In cooperation with the U.S. industry, NASA is developing propulsion technology to reduce the environmental impact of future commercial engines through reduced combustor emissions. The

goal of the Emissions Reduction project is to reduce takeoff and landing nitrogen oxide emissions in Phase 1 by at least 50 percent relative to 1996 ICAO limits over current combustor technology and with comparable cruise emission reductions; the Phase 2 goal is a 70-percent nitrogen oxide emissions reduction. Research will focus on both large and regional-class engines. These future engines will operate at overall cycle pressure ratios up to 50:1, peak cycle temperatures of 3,000 degrees Fahrenheit or greater, and very high bypass ratios of up to 20:1. The low-emission combustor technologies will be incorporated into the design of future engines entering into service in or after the year 2005 and will be transitioned into derivatives of engines currently in service.

Aviation-related atmospheric research includes a quantitative assessment of the environmental impact of subsonic transport aircraft fleets. In the Environmental Assessment project, sensors are placed on NASA research aircraft for in situ measurement in the troposphere. Existing sensors are used; however, new sensors are developed as necessary. The gathered data support validation of the atmospheric chemistry and climate models developed in cooperation with the Earth Science Enterprise.

Aviation Systems Capacity. The major challenges to increasing throughput in the Nation's aviation system are to accommodate projected growth in air traffic while preserving and enhancing safety, provide all airspace system users with more flexibility and efficiency in the use of airports, airspace, and aircraft, reduce system delays, enable new modes of operation that support the FAA commitment to "free flight," and maintain pace with a continually evolving technical environment. The goal of this investment area is to enable safe increases in the capacity of major U.S. and international airports through enabling improvements to, and modernization of, the air traffic management system, as well as the introduction of new vehicle classes whose operation can take advantage of the improved, modern air traffic management system. Research is focused on two areas: (1) developing advanced concepts, technologies, and operational concepts that enable new aircraft, and (2) enabling the implementation of operational concepts and their associated decision support tools, procedures, and hardware systems to assure safety and maximize efficiency, flexibility, predictability, and access into operations in the airspace system.

The U.S. aviation industry is investing \$6 billion over 20 years to increase airport capacity. However, there is a gap between the industry's desired capacity and the ability of the National Airspace System to handle the increased air traffic. In addition, current FAA standards require a reduction in terminal operations during instrument-weather conditions at many airports, causing delays and reducing airport productivity, which increases the cost of operating aircraft. The objective of the Terminal Area Productivity project is to safely achieve clear-weather capacity in instrument-weather conditions. In cooperation with the FAA, NASA's approach is to develop and demonstrate airborne and ground technology and procedures to safely reduce spacing requirements, enhance air traffic management and reduce controller workload, improve low-visibility landing and surface operations, and integrate aircraft and air traffic systems.

An efficient and effective air traffic management system is vital to the U.S. transportation infrastructure. U.S. airlines estimate that limitations in the current system cost \$3.5 billion annually and thousands of hours of delays. In alliance with the FAA and industry, the objectives of the Advanced Air Transportation Technology project are to enable "free flight" operational concepts through the application of advanced air traffic decision support technology, as well as advanced flight deck decision management technology. The FAA has two phases of free flight: an early implementation

of the architecture by 2005 and a "mature free flight" architecture that would be available 10 to 20 years later. While supporting implementation of the 2005 architecture, the challenge to this project is to demonstrate aspects of "mature free flight" ahead of its expected availability. The long-term benefits are reduced operational costs and a larger aviation market both nationally and in countries where air traffic efficiency is limited. NASA plays a pivotal role by leveraging its expertise in human factors, information technology, and automation technology to develop and validate high-risk elements of new air traffic concepts.

Civil Tiltrotor offers a unique opportunity to create a new aircraft market while increasing capacity by offloading major airports of a large portion of the short-haul traffic. Studies conducted by Boeing Commercial Aircraft for NASA and the FAA and by various state and local transportation authorities (such as the Port of New York and New Jersey Authority) have shown the civil tiltrotor to be a viable candidate for air traffic congestion relief. This project is an initial effort to develop the most critical technologies to enable civil tiltrotor development: noise reduction, cockpit technology for safe, efficient terminal area operation, and contingency power for one engine inoperative operation.

Reduced Seat Cost. A major challenge to reducing ticket prices and increasing the mobility of the traveling public is to reverse the trend of increasing aircraft ownership and operating costs. Dramatic time and cost savings in development, production, and certification are essential to achieve the significant reductions in aircraft costs necessary to make air travel more affordable. The AST program, in conjunction with industry, is aimed at reducing acquisition costs, operation costs, and design cycle time. NASA's test facilities and core expertise in materials, structures, aerodynamics, propulsion, analytical methods, and computational tools are key elements in addressing these critical issues. NASA's research is focused on innovative design techniques and structural concepts to enable the U.S. aviation industry to significantly advance today's state of the art for aircraft and engines.

Current approaches to the aerodynamic design of commercial transports rely on independent design and test phases, resulting in design cycles that are both long and expensive. The Airframe Methods and Design Environment Integration project is developing technology for efficient, integrated design and test phases, enabling significant aerodynamic design cycle time reductions and shortening the total aircraft development time as compared to 1995 practices. The resulting decreased time to market allows new, less expensive technologies to be incorporated faster. In addition, the new design and test procedures are used to validate and deliver highly efficient wing designs for cruise and low-speed operation, including the effects of propulsion system integration, and will provide a significant reduction in aircraft operating cost relative to the 1995 baseline aircraft.

In cooperation with the U.S. industry, the Engine Systems project is developing propulsion technology to reduce turbine engine design and development cycle time and improve the performance and affordability of future engines. Research will focus on high-pressure compressors, high-pressure turbines, and high-temperature disk and blade materials to obtain overall cycle pressure ratios up to 50:1, peak cycle temperatures of 3,000 degrees Fahrenheit or greater, and composite components and advanced lubrication to enable very high bypass ratios of up to 20:1 for these advanced low-noise turbofan engines.

The Systems Evaluation project will provide assessments of the impact of alternative AST technologies on the integrated aviation system. Such assessments are used to evaluate the results and benefits of AST technologies relative to reduced seat cost and to understand the cost-benefit relationships among the AST technologies to ensure knowledgeable application. These assessments also assist NASA management in program investment decisions and benefit Enterprise customers in understanding technology impact and potential in an integrated aircraft and system. A client-based computerized system with fully integrated architecture and aviation system models and databases is developed to provide NASA the assessment of potential technology benefits.

The Airframe Materials and Structures project is focused on developing methods and tools for cost-effective composites application to transport aircraft. The goal is to validate the manufacturing methods for a semispan composite wing. Through a manufacturing proof-of-concept test, this project will validate technology for cost-effective methods to fabricate composite wing cover panels. The goal is a 10- to 25-percent weight reduction and a cost savings of 20 percent compared to today's metallic transports.

General Aviation. General aviation technologies are targeted to improve the safety, utility, ease of use, and reliability of the next generation of general aviation aircraft for business and personal transportation. The Advanced General Aviation Transportation Experiments (AGATE) Consortium supports general aviation industry revitalization through the development and application of new technology for greater availability of small transportation aircraft to more travelers for business and personal use. The consortium focuses on reducing the cost of personal small aircraft transportation. The outcome sought is an expanded role of general aviation through higher use of the airspace and the large network of general aviation public-use airports that serve thousands of small communities and rural areas in the Nation. Key elements of technology development include improved safety, environmental compatibility, advanced user-friendly cockpits, advanced controls, performance efficiency, and lower initial and operating costs. Safety-related technologies include improved icing avoidance and protection systems and advanced human interfaces using flat panel displays.

Space Transportation Research and Technology Program:

Space Transportation R&T is a balanced effort to develop the technologies to support the Aero-Space Technology Enterprise's access to space and in-space transportation goals. Building on technology development in the Aeronautics Base R&T and developing the core technologies necessary for space transportation is the Advanced Space Transportation program (ASTP). Validation of these technologies is key to ensuring the development of next-generation launch and space platforms. The RLV program provides X-vehicle demonstrators for validating key technologies in an operational environment.

Advanced Space Transportation Program. The objective of ASTP is to develop, mature, and ready the core technologies needed for the success of the flight demonstration projects. The primary purpose of ASTP is to develop and demonstrate technologies and raise their TRL from 1 to 5. These efforts range from the observation and reporting of basic technology principles to the component and/or breadboard validation in a laboratory environment. Technology validation in relevant flight environments (TRL 5 to 7) will be accomplished by the flight demonstration projects.

While the flight demonstration projects define many of the ASTP-focused technology efforts, ASTP also pursues the development of revolutionary advancements in space access with the potential to reduce costs to hundreds of dollars per pound of payload versus the thousands of dollars measured today. In short, ASTP provides the basic building blocks of propulsion and airframe systems technologies to support flight demonstration projects, while focusing on future breakthrough technologies beyond the next generation.

The top-level objective to reduce space transportation cost expands into three key technology objectives: reduced system acquisition costs, reduced system operations costs, and increased system performance. Low-Earth orbit launch costs are driven by: (1) amortization of development costs; (2) complex operations, including the assembly and checkout of numerous complex interfaces; (3) maintenance, checkout, and perpetual product improvements driven by high-reliability requirements on nonrobust and inherently unreliable systems; (4) limited reuse; and (5) low launch rates. High launch costs prevent high launch rates, which would lower the cost of reusable systems. Low life-cycle cost will result from technology maturity through system-level demonstration prior to full-scale development, highly integrated simplified designs, robust margins, long service life, and high operability.

Figure 9.3-1 shows these technology objectives generally distributed from near term to long term against the major ASTP projects. For example, "small payload focused" technologies are aligned with the near-term objectives of reducing vehicle acquisition cost and reducing vehicle operations cost, whereas "space transportation research" is primarily aligned with long-term objectives of increased performance to enable new missions. Many objectives are applicable to both launch and upper stages, but there are many unique propulsion objectives for upper stages. Current technology efforts are distributed across all program objectives. Systems analysis will be used to calculate quantitative measures of the contribution of each task to the objectives and, finally, to the reduction in overall cost.

The 1986 National Commission on Space noted critical technologies required to build the technology base for the "highway to space," including: low-cost manufacturing of critical components; vigorously extending the technology base for both rocket and air-breathing propulsion; durable thermal protection systems; lightweight materials and structures; improved information, guidance, and control; and, for in-space, long-life reliable hydrogen/oxygen propulsion, nontoxic storable chemical propulsion, electric/ion propulsion, aerobrake technologies, adaptive, fault-tolerant avionics, tethers, and in situ propellant production. This list of technologies was used as a starting point to assess technology needs from the various customer classes mapped against candidate transportation vehicle concepts.

This assessment resulted in the structuring of the ASTP into four projects: Low-Cost Technologies, aligned with the near-term objectives of reducing vehicle acquisition cost and reducing vehicle operations cost; Advanced Reusable Technologies, primarily aligned with increased vehicle performance; Space Transfer Technologies, focused on technologies that are unique to propulsion

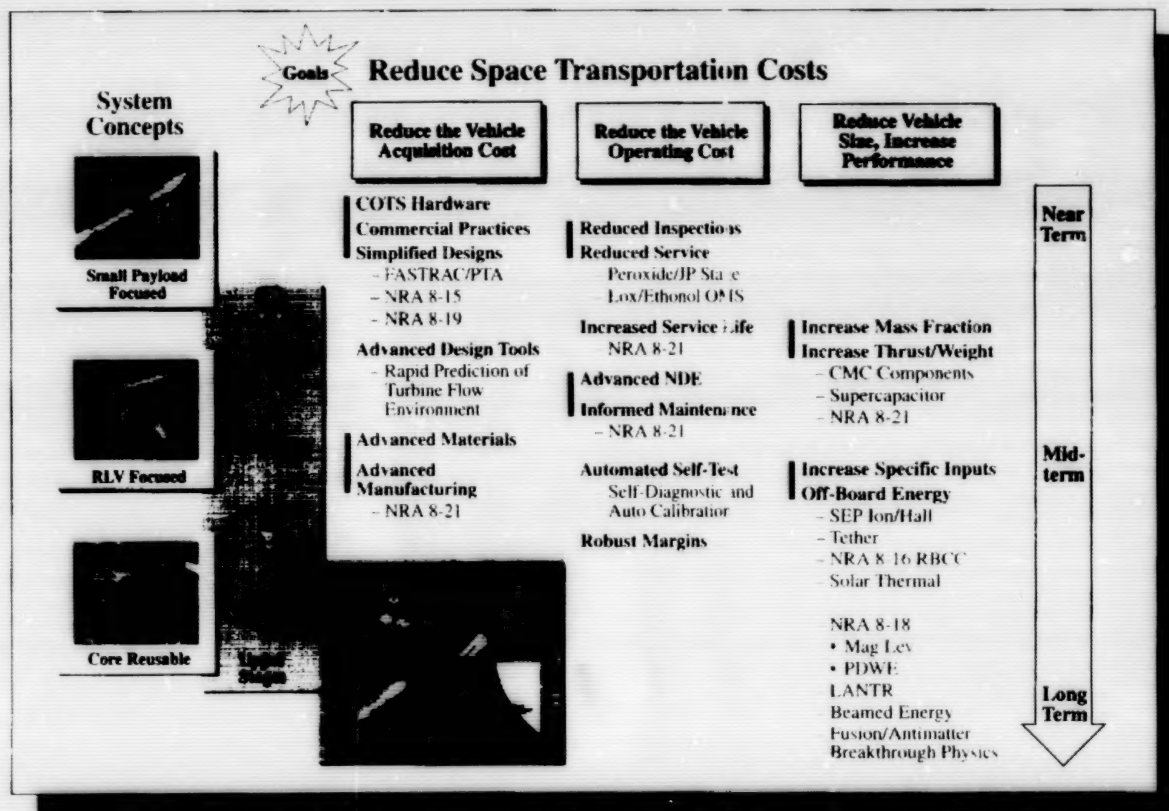


FIGURE 9.3-1. ADVANCED SPACE TRANSPORTATION PROGRAM TECHNOLOGY OBJECTIVES

objectives for upper stages; and Space Transportation Research, which will pursue proof-of-concept research in revolutionary technology areas that may lead to dramatic reductions in the cost of access to space or enable new interplanetary or interstellar space missions. Figure 9.3-2 presents the overall ASTP roadmap and shows the time-phase I integration of the core and focused technology activities into candidate vehicle concepts that respond to the technology challenges.

Low-Cost Technologies. The Low-Cost Technologies project is focused on the near-term technology challenge of reducing hardware acquisition and operations costs. The "small payload focused" activity primarily supports near-term customers with small science and technology payloads (approximately 150 kilograms) with long-term applications to all future launch systems, including very large payloads and including human exploration, military, and large commercial space platforms.

Research is directed at innovative, simple design approaches for low-cost manufacturing and operations, aerospace applications of commercial off-the-shelf hardware practices, and system design solutions that incorporate robust margins. This will lead to space transportation hardware that does not require the highly specialized, labor-intensive manufacturing, checkout, and maintenance operations of current space transportation systems and could take advantage of the economies of scale available in commercial processes.

Over the last few years, NASA has expended significant resources to reduce the size, cost, and development time associated with science payloads. In addition, the university science community

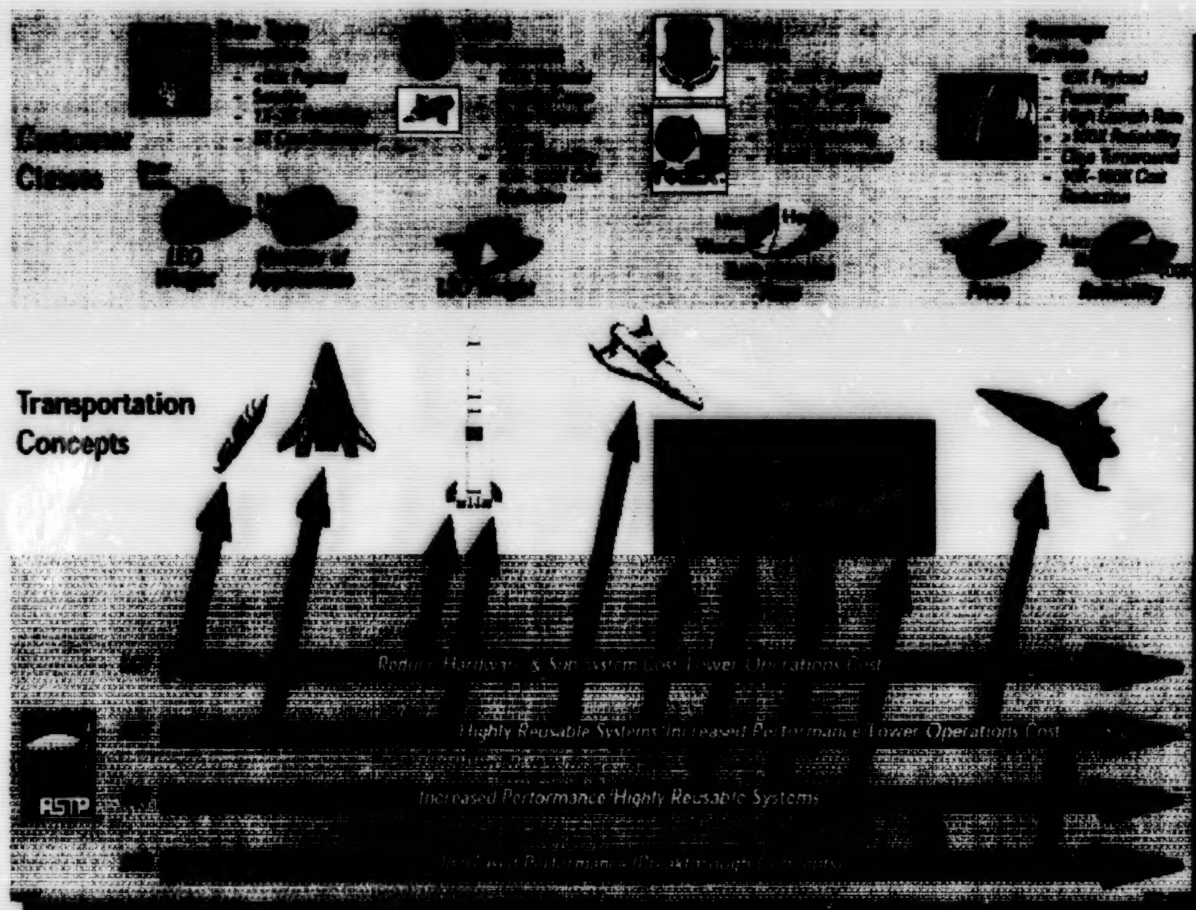


FIGURE 9.3-2. ADVANCED SPACE TRANSPORTATION PROGRAM ROADMAP

has identified the desire to begin launching 4 to 6 university explorer-class (UNEX) missions per year after the turn of the century. These payloads will incorporate important emerging technologies, cost only a few million dollars to develop, and rejuvenate the university science community; however, they can only be accomplished with the availability of a low-cost launch system. To meet this emerging need, NASA solicited industry proposals for a technology development and demonstration program that will invest in innovative technologies for low-cost manufacturing and systems engineering, which will lead to space transportation hardware that does not require the highly specialized, labor-intensive manufacturing and operation of current space transportation systems. The focus is on the major hardware cost drivers—the propulsion system as well as the application of commercial-off-the-shelf hardware to traditional high-cost aerospace components. The key technology effort will provide a flight engine (FASTRAC) for the X-34 with a production cost goal of \$500,000 per engine.

Advanced Reusable Technologies. The Advanced Reusable Technologies project is focused on the access to space challenges of reducing costs by two orders of magnitude in the long term. Technology objectives include long-life, high reusability, and operability of space launch systems. Long-term core technology development addresses propulsion and airframe systems.

The initial focus for Core Propulsion Systems project has been on air-breathing rocket-based combined cycles because of their potential to substantially increase engine performance over the pure rocket system. Four rocket-based combined-cycle concepts have been selected for preliminary

proof-of-concept ground testing up to Mach 8 in FY 1998. The next phase, if warranted by the test results, will be the development and ground testing of a "flight-weight" engine for further vehicle synthesis and could possibly lead to a flight demonstration effort. Future technology investments will focus on advanced materials to reduce weight and improve engine life, advanced nozzles to improve performance, and turbomachinery technologies to improve reliability and engine life. The aim is to mature technologies through ground testing and analyses to the point where they can be considered for flight evaluation.

The Core Technology Airframe Systems project is pursuing the maturation of highly reusable airframe and structures technologies for RLV's. Airframe systems technologies include structures and materials, cryogenic tanks, thermal protection systems, avionics/operations, and system analysis, design, and integration. Research is being conducted in advanced composites and refractory composite hot structures development, technologies for both structure and cryotankage joints, ultrahigh-temperature ceramic thermal protection materials, instrumentation for vehicle health monitoring, and highly reliable avionics systems.

Since the initiation of the X-33 and X-34 vehicle developments and flight test programs, additional technology approaches have been identified that, if matured, would enhance the development of an operational RLV. Major areas for "RLV focused" technology developments include interdisciplinary vehicle synthesis and optimization, large airframe structures and advanced materials, durable thermal protection systems, long-life main propulsion subsystems, and advanced avionics and integrated vehicle health management technologies. Potential customers of the RLV focused technologies are the commercial launch vehicle developers of a new RLV to upgrade or replace the Space Shuttle. The customers of the core technologies will include commercial developers of a very low-cost, highly operable, and reliable launch system that will open the "highway to space" for revolutionary space business ventures.

Space Transfer Technologies. Space Transfer Technologies projects are focused on space transportation application within Earth orbit and beyond. This project of the ASTP is focused on the challenge of reducing the cost of orbit transfer and interplanetary transportation by one order of magnitude and decreasing trip time by a factor of 2 to 3. The technology challenge is improved propulsion system performance with reduced propulsion system mass. Approximately 70 percent of the required launch mass is the propellant required to take the payload to its final destination. A reduction in this propellant mass would reduce launch as well as space transfer costs. Reduced trip times will result from increased propulsion efficiency, reducing the risk for exploration missions. Exploration initiatives such as the New Millennium program are focused on miniaturizing spacecraft, but the advantage will not be realized unless the spacecraft propulsion reaches efficiencies that allow for reductions in size and mass.

The program supports the design and ground testing of the NASA Solar Technology Application Readiness (NSTAR) ion engine to be flown on the New Millennium Deep Space 1 spacecraft in 1998. NSTAR will validate ion propulsion for future robotic planetary missions. The project also supports technology work in the area of advanced electric and thermal propulsion systems for Earth orbit and planetary transfer, technologies for atmosphere-assisted entry for planetary missions and Earth-orbit return, cryogenic fluid management for orbit transfer and exploration missions, and nonconventional orbit transfer systems, such as electrodynamic tethers. Advanced

ion and Hall-effect thruster developments will continue, with emphasis on increased cathode life and improved power processor designs. A 10-kilowatt breadboard system will be assembled and tested for potential application to next-generation satellites. Minor investments will begin in technologies for atmosphere-assisted entry for planetary missions and Earth-orbit return.

Space Transportation Research. The Space Transportation Research project is focused on the challenge of enabling new missions. The approach is to develop advanced concepts for enabling breakthroughs in space transportation via small, critical technology experiments and breadboard validations. This effort provides the basic research function and relies on partnerships with industry, universities, other agencies, and NASA Centers to identify longer term technologies with tremendous promise for dramatic improvement in propulsion performance and cost reduction. Areas of interest include magnetic levitation for launch augmentation, pulse detonation engines, high-energy propellants, effective use of offboard energy sources, and advanced propulsion concepts and materials that hold promise for enabling exiting new missions that are beyond the realm of present technological capability.

Advanced Propulsion Concepts. The Advanced Propulsion Concepts project is intended to provide the data needed to guide future investments in propulsion technology to enable reasonable timeframes for missions to the edge of this solar system and toward interstellar voyages. The needed data are obtained by performing analyses and experiments to investigate the promise and feasibility of candidate concepts. A large number of concepts have been examined in the past; all but a few have been determined to be nonfeasible, because either they offered no increased benefit, they were technically infeasible, or sufficient capability in a supporting technology (as in materials) was not yet in place. Once the benefit and feasibility of a candidate breakthrough have been established, it is ready to be incorporated in the mainstream advanced technology program. Specific technology concepts being pursued include antimatter catalyzed fission/fusion, dense plasma focus, novel propellant storage, lithium-fueled Lorentz force accelerators, and micro-propulsion.

Reusable Launch Vehicle Program. Consistent with the Administration's space policy and the results of the NASA access to space study, the RLV program provides for the incremental technology development and flight demonstrations of systems concepts that will provide the reusability, operability, reliability, launch abort, and performance required to support an end-of-the-decade decision on the appropriate approach to a commercial launch system. Such a system would have the potential to achieve the access to space near-term goal of an order-of-magnitude reduction in launch costs. Figure 9.3-3 presents the overall RLV roadmap and shows the integration of the key components leading to the joint Government-industry decision regarding the development of a fully reusable launch system.

X-34. The X-34 is an advanced technology demonstration vehicle aimed at reducing the risk of future operational reusable launch systems and permit the full utilization of space transportation technology advances. Initiated in the summer of 1996, with a first flight scheduled in March 1999, the X-34 will be launched from a carrier aircraft and fly at speeds up to Mach 8. It will be operated as a testbed to demonstrate key embedded technologies as well as technology experiments and aerosciences research. The primary embedded technologies included in the X-34 program include:

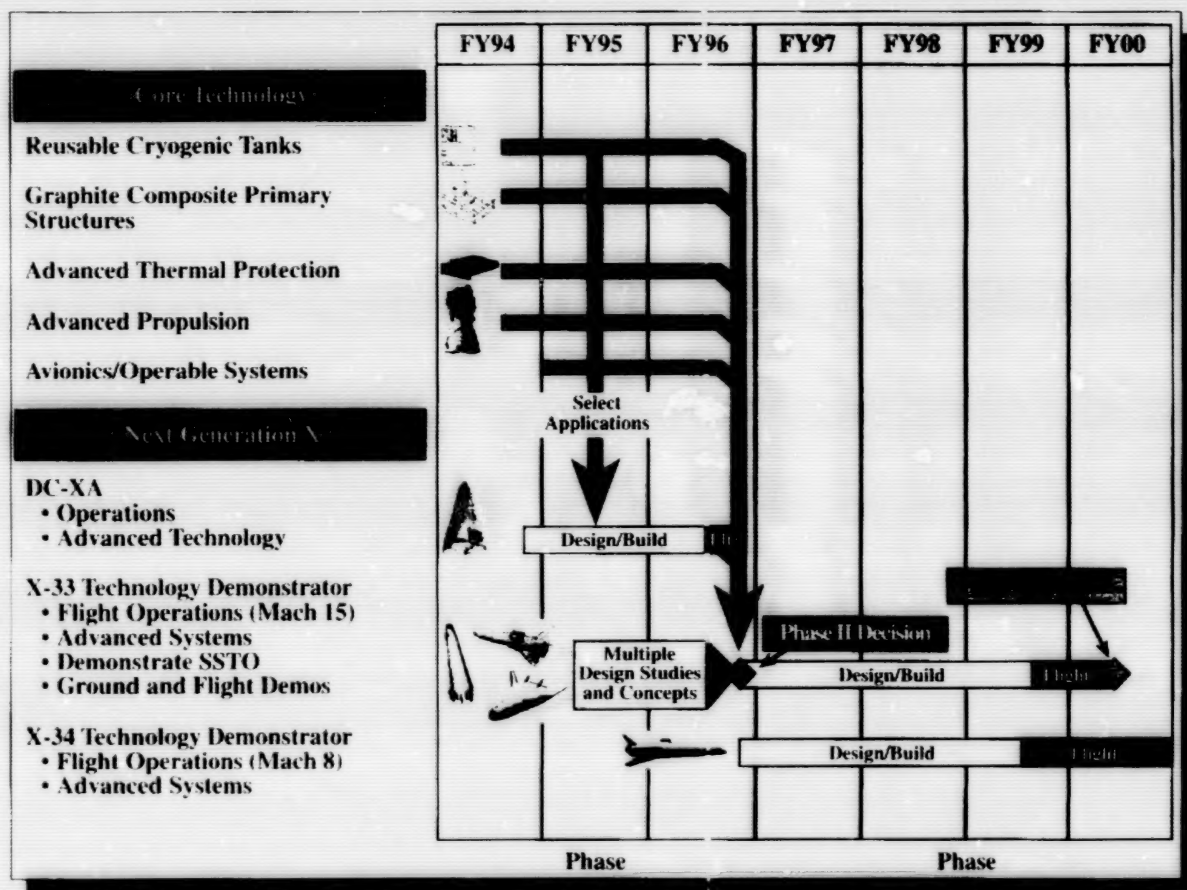


FIGURE 9.3-3. REUSABLE LAUNCH VEHICLE ROADMAP

- A composite airframe, including primary structure, aerosurfaces, and thrust structures, with the high-margin structure designed to require minimal inspection, given its modular design and numerous access ports for maintainability
- Composite reusable propellant tanks and propulsion system elements
- Reusable propellant tank cryogenic insulation
- Low-cost, low-weight thermal protection systems and materials using Silicone Impregnated Reusable Ceramic Ablators on leading edges and other critical heating areas and silica cloth/silica fiber quilts over the large lower heating surfaces—new ceramic thermal protection systems being far less expensive than either the current Shuttle ceramics or an advanced metallic system but undemonstrated in operational environments
- Low-cost, flight-proven avionics, including differential Global Positioning System (GPS) guidance and integrated GPS/INS (Inertial Navigation System)—critical technologies because the X-34 and future RLV's will depend heavily on automatic navigation, guidance, and control for autonomous landing
- Integrated vehicle health monitoring system with rapid software reprogramming to make the X-34 capable of rapid turnaround

The flights will demonstrate advanced reusable space transportation technology and validate the streamlining of maintenance, repair, checkout, and other operations that traditionally add tremendous cost to launch vehicle systems. X-34 technical goals include flexible integration capability, a

high flight rate (25 flights per year), autonomous flight operations, a safe abort capability, and a recurring flight cost of \$500K or less.

X-33. A major part of the RLV program, the X-33, is a larger and more aggressive experimental flight demonstration than the X-34. It combines business planning with ground and flight demonstrations of advanced structures, materials, and propulsion system technologies to (1) mature the technologies required for a next-generation reusable system, (2) demonstrate the capability to achieve low development and operational costs and rapid launch turnaround times, and (3) reduce business and technical risks to encourage significant private investment. Lockheed Martin Skunk Works was selected to design, build, and fly the X-33 test vehicle, demonstrate other key technologies, and mature the business and commercial venture plans. The Lockheed Martin team is pursuing a vertical takeoff, horizontal landing lifting-body configuration that uses a linear aerospike main engine system and an integrated lifting-body shape. The half-scale experimental demonstrator will begin flight testing by the end of the decade.

In addition to those technologies critical to single-stage-to-orbit operation, the X-33 will focus on those operational issues that are critical to the development of reliable low-cost reusable space transportation. The X-33 ground support and flight control systems are being designed to accomplish the operations and supportability goals that are key to lower cost system operations. The operability and performance demonstrated by the X-33 will provide the necessary data to establish the detailed requirements for a future operational RLV.

The primary technologies that are enabling the X-33 are:

- Reusable, lightweight composite airframe and cryogenic tank structure, insulation, and thermal protection system
- Durable, metallic thermal protection system (Inconel, PM 2000)
- Oxidation-resistant carbon-carbon hot structures
- Graphite composite liquid hydrogen (flight demonstration) and liquid oxygen (ground test) tanks
- Aerospike propulsion system (flight) and other critical components meeting the RLV engine thrust-to-weight and operability requirements (ground)
- Integrated vehicle health management (system architectures, diagnostic and prognostic software capabilities for on-vehicle FDIR, sensors, effectors, and test equipment)
- Automated ground operations and maintenance techniques
- Automated flight and landing operations capability

To date, the X-33 program has completed system and subsystem preliminary design reviews, completed critical design reviews, completed the Environmental Impact Statement in less than 1 year, initiated final assembly of the X-33, and started construction on the launch site at Edwards Air Force Base in California. Critical elements of the fuel tanks, including the composite joints, have passed structural load testing and are proceeding well. The oxidizer flight tank has been through fabrication, assembly, and checkout testing and has now been delivered to the X-33 vehicle assembly facility in Palmdale, California.

Future Space Launch Studies. The National Space Transportation Policy calls for an end-of-the-decade decision on pursuing an operational launch system to reduce NASA's launch costs. To

support this decision, industry-led future space launch studies will be undertaken to provide input to NASA and the Administration on an appropriate approach. Industry inputs will be accomplished through a request for proposals with terms of reference approved by the Administration. Separate efforts being undertaken, such as the Crew Rescue Vehicle for the ISS, Future-X demonstration strategy, and possible business plans for X-33 Phase III, would contribute to these studies.

Future-X Series Technology Demonstrations. As part of NASA's core mission to advance the state of the art in aeronautics and space transportation, the Agency will continue to develop and demonstrate advanced technologies through the use of experimental flight vehicles. The primary objective of Future-X is to flight demonstrate technologies that can dramatically reduce the cost and increase the reliability of reusable space launches by an additional order of magnitude over the next 20 years and achieve our enabling technology objectives for in-space transportation systems.

It is envisioned that Future-X flight demonstrations will build on ASTP core technologies by advancing technology development in the following areas:

- Rapid, low-cost payload integration
- Atmospheric aeroassist
- High specific-impulse orbital engines
- Durable thermal protection systems
- Zero-g cryogenic fluid management
- High-temperature structures
- Long-life airframe systems
- Alternate propulsion fuels/densification
- Air augmented rocket engine systems
- High lift/drag ratio external moldlines
- Automated orbital operations (including rendezvous and docking)
- Rapid turnaround processing
- Ultrahigh-temperature, leading-edge thermal protection systems
- Advanced vehicle health monitoring

9.4 Office of Aero-Space Technology Approach to Defining Program Priorities

Once the Enterprise goals have been defined, the program development begins with an investment strategy that describes the key issues, technology gaps and solutions, and current Enterprise and partner capabilities (Figure 9.4-1). The result is an integrated set of areas of investment for the particular goal.

Following the investment strategy, the development of a portfolio of Enterprise investments begins. Because the investment strategies of the Enterprise overlap in some key areas, a process of integration of all Enterprise investment strategies is required. As investment portfolios are typically limited with funding, several questions need answers to ensure an appropriate balance in terms of national benefits versus system/customer needs, Enterprise goals, midterm versus far-term research, current state of the art, and the urgency to which particular areas need addressing.

The tools at the Enterprise's disposal to address these areas include system studies, current program assessments, customer, partner, and stakeholder inputs, Agency directions, and the capability of the NASA Centers.

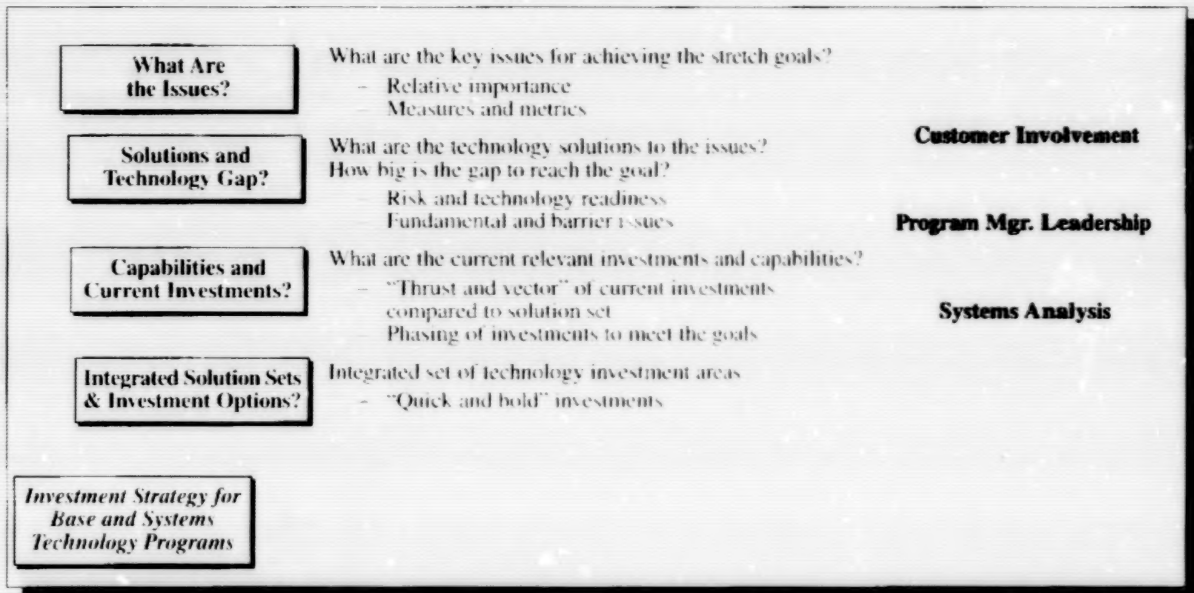


FIGURE 9.4-1. OFFICE OF AERO-SPACE TECHNOLOGY INVESTMENT STRATEGY

The program planning and implementation phases of portfolio development are shown in Figure 9.4-2. The result of investment strategy integration is a set of program development statements. The program development statements kick off the program planning by identifying the national goal(s), the proposed program goals, objectives and completion dates, results of system benefit studies, and rough order magnitude resources. The Aero-Space Technology Executive Board reviews the program development statements and directs detailed planning to support a program readiness review. A team prepares a high-level program plan that includes program description and justification, elements of the program, customer and partner support, the management approach, detailed resource estimates and validation of the estimates, risk assessment, products and metrics, and any significant issues that arise. The purpose of the program readiness review is to ensure that the program plan has a solid technical and cost basis and satisfies NASA management requirements.

An independent team of experts reviews the program plan and makes recommendations to the Executive Board on how the program should proceed. The Executive Board directs that the program planning continue to the next level of detail. If appropriate, the resulting program may be required to be reviewed by a nonadvocate review team.

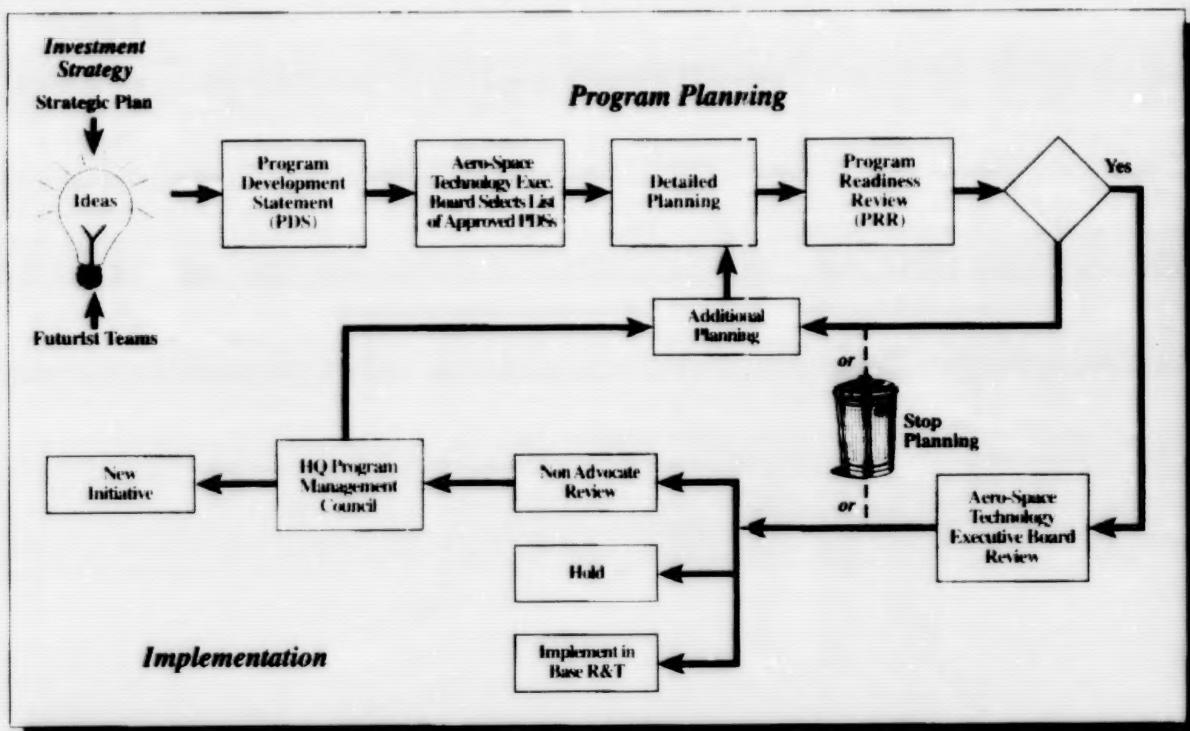


FIGURE 9.4-2. OFFICE OF AERO-SPACE TECHNOLOGY PROGRAM DEVELOPMENT



10. Technology Transfer and Commercialization

The purpose of this section in the NASA Technology Plan is to explain NASA's technology transfer and commercialization mission per the *Agenda for Change*, define the overarching technology transfer and commercialization process for guiding each Enterprise's efforts, describe the NASA Commercial Technology Network's role in supporting these efforts, and establish the common metrics to be used in evaluating progress.

10.1 *Agenda for Change*—NASA's Commercial Technology Policy

When NASA issued its *Agenda for Change* in 1994, it elevated technology transfer and commercialization to a primary mission, concurrent to and comparable in importance to its aeronautics and space missions. NASA further solidified the mission's importance with the May 1996 issuance of its Commercial Technology Policy, a companion document to the *Agenda for Change*.

These two documents established a new way of doing business for NASA technology transfer and commercialization by creating a mix of practices and mechanisms that enable the Agency to more closely align its way of doing business with that of the private sector. The common denominator in these practices is technology partnerships. Technology partnerships are business arrangements among the Government, industry, and/or academia, wherein each party commits resources to the accomplishment of agreed-to objectives and shares the risks and rewards of the endeavor.

As seen in Figure 10.1-1, each Enterprise is responsible for including technology transfer and commercialization as part of its overall technology plan. The intent is for each Enterprise to proactively focus on technology transfer and commercialization from the very start, so as to maximize

the potential commercial utilization of its new technologies and innovations. As shown in Figure 10.1-1, achieving this "maximum leveraging" of NASA technologies requires the inclusion of not only our traditional aerospace partners but also the nonaerospace community and other Federal agencies.

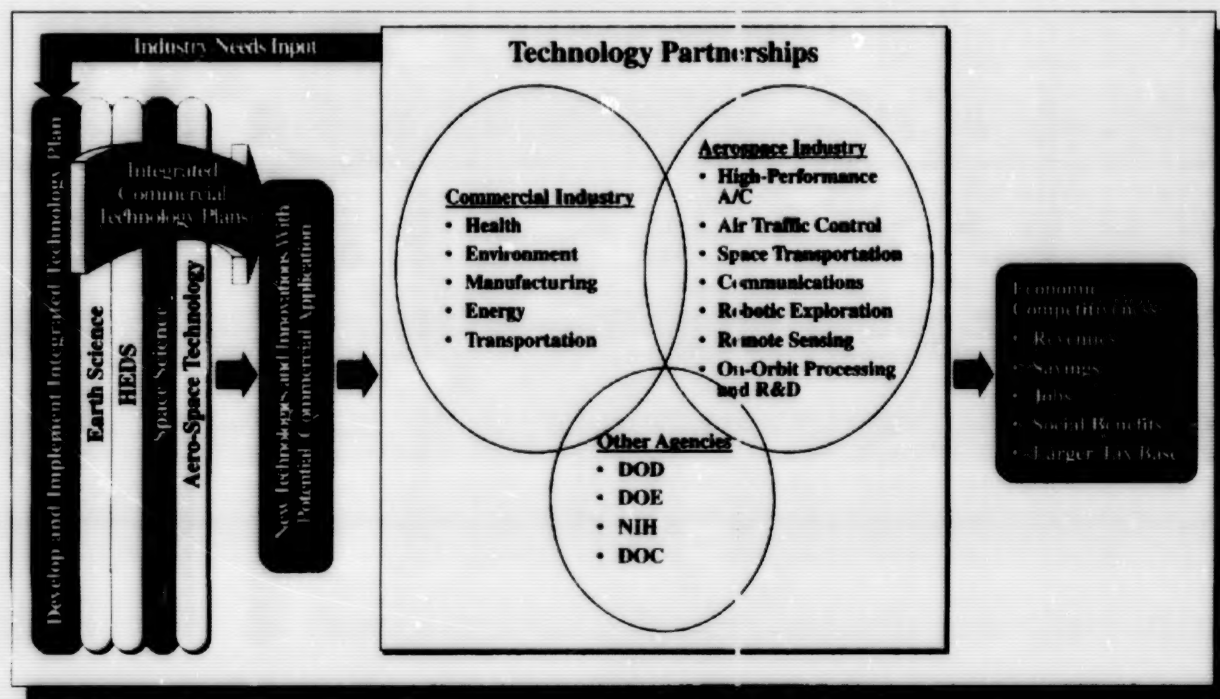


FIGURE 10.1-1. NASA TECHNOLOGY TRANSFER AND COMMERCIALIZATION

10.2 Guideline Process for the Enterprises

Figure 10.2-1 illustrates the NASA commercial technology process. All NASA programs and projects are subject to the process, whose end objective for each program or project is the same—that of maximizing each program's or project's commercial impact. As shown in Figure 10.2-1, NASA's commercial technology process is not a stand-alone process; it is integral to and is accomplished within the Agency's overall strategic planning and management process. This not only includes the Agency's technology planning process but also the Agency's program and project management process (NPG 7120.5).

Again, the intent of the Agenda for Change is to proactively and systematically emphasize technology commercialization from the very start of a technology program via proactive technology partnerships rather than a passive and serendipitous "trickle-out" approach. A key element is for each Enterprise to ensure that where appropriate, individual programs and/or projects should contain strong technology commercialization plans that implement this process. One such model is the technology commercialization emphasis contained in the Small Business Innovative Research (SBIR) program. Because the SBIR program cuts across all Enterprises, each Enterprise already has a working model that it can apply as is or tailor to other Enterprise programs. This process is more fully explained in the *NASA Technology Transfer and Commercialization Handbook*.

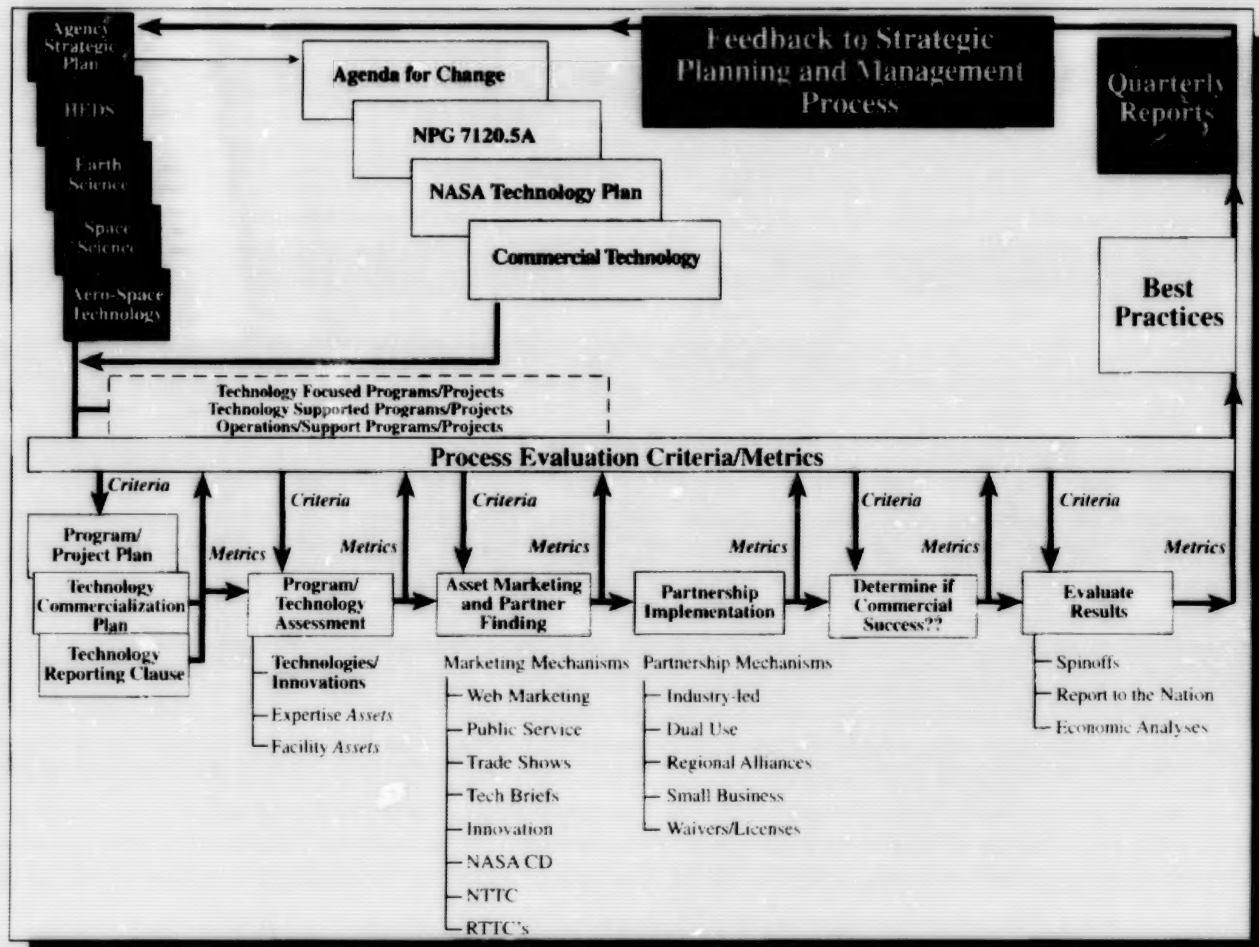


FIGURE 10.2-1. NASA COMMERCIAL TECHNOLOGY PROCESS

10.3 NASA Commercial Technology Network

Another of the *Agenda for Change*'s key elements is the NASA Commercial Technology Network (NCTN). This network exists solely as a resource to support NASA's technology transfer and commercialization mission (Figure 10.3-1). As such, it is to be utilized by each Enterprise. Basically, the NCTN consists of:

- Center-based Commercial Technology Offices
- Regional Technology Transfer Centers (RTTC)
- Commercial Technology Incubators
- National Technology Transfer Center (NTTC)
- NASA Commercial Technology Management Team (NCTMT)
- An electronic network—NASA TechTracS/NCTMT management intranet

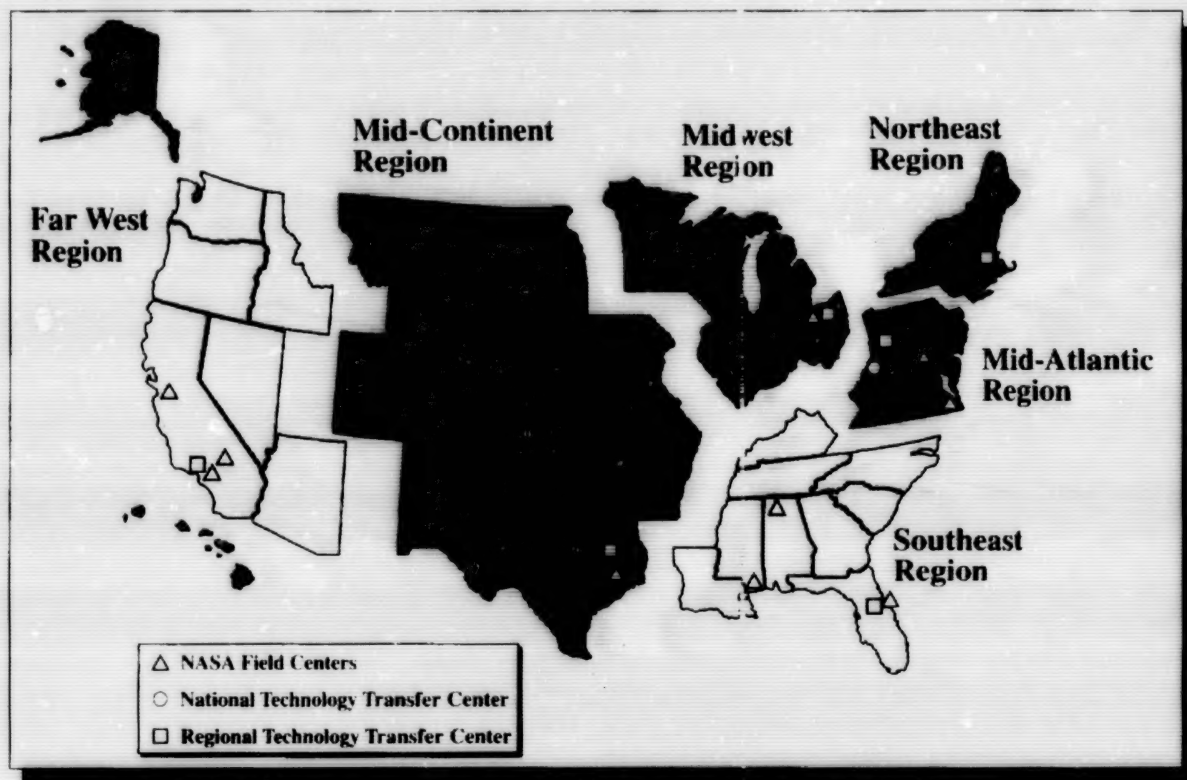


FIGURE 10.3-1. NASA COMMERCIAL TECHNOLOGY NETWORK

To guide and manage the NCTN, NASA has established the NASA Commercial Technology Management Team (NCTMT), which consists of a representative from each Enterprise and from each Center's Commercial Technology Office.

10.4 Technology Commercialization Metrics

The definition and utilization of technology transfer and commercialization metrics are required by both the National Performance Review and the Agenda for Change. The NCTMT has established and produces a core set of technology metrics traceable to the technology transfer and commercialization process discussed previously. Figure 10.4-1 shows our hierarchical metrics model.

Metric data are systematically collected for the first five tiers of this model. These metrics provide a common baseline by which each Enterprise can evaluate the effectiveness of its technology transfer and commercialization plans so as to achieve continual improvement. Tiers 6 and 7 metrics are much more complex and are examined with periodic analyses. The first five tiers are described here in more detail:

1. *Program/Project Strategy*—This metric tracks which programs and projects are emphasizing via technology transfer and commercialization plans. For example, as discussed earlier, each Enterprise's SBIR program falls into this category.

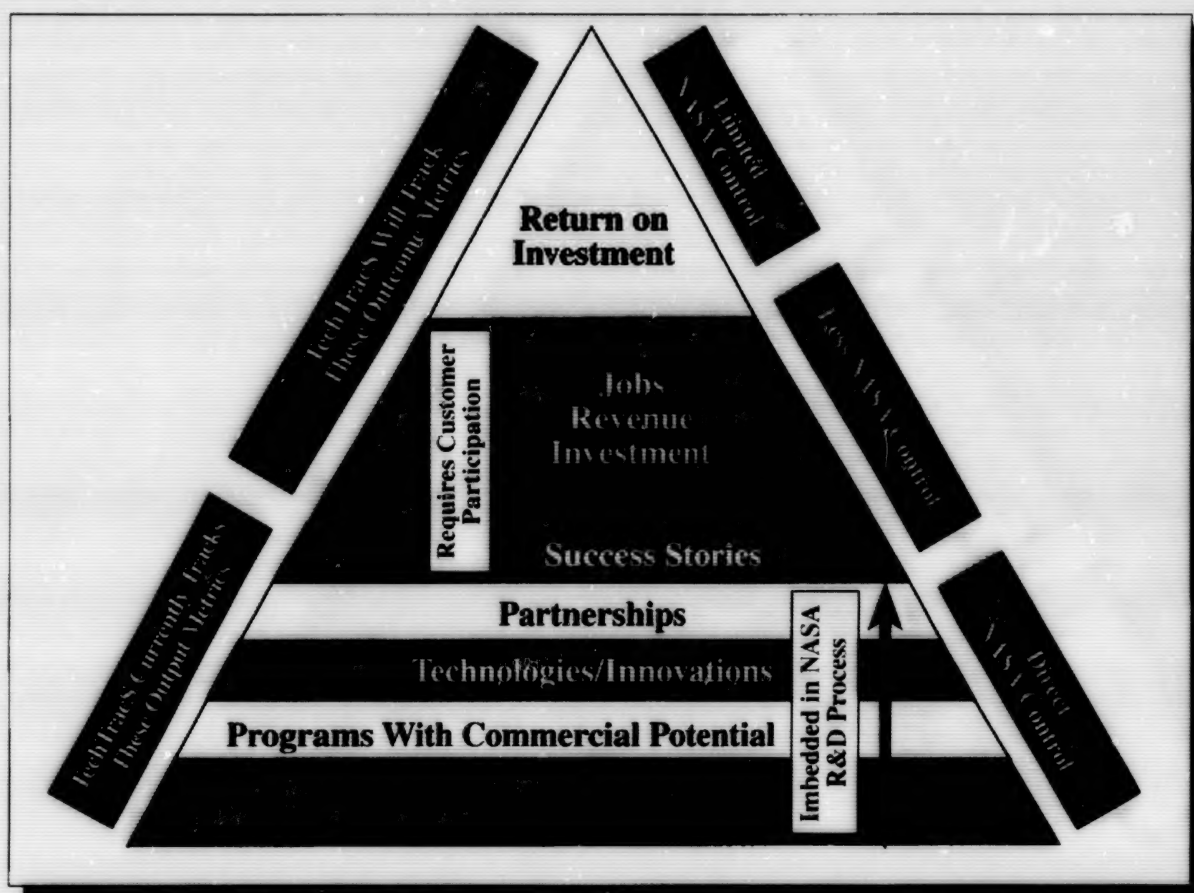


FIGURE 10.4-1. NASA TECHNOLOGY COMMERCIALIZATION METRICS

2. *Programs With Commercial Potential*—This metric determines what portion of each Enterprise's activities is to be tracked for commercial potential regardless of whether the activity has a plan or just a technology reporting clause. Currently, about 80 percent of NASA's activities are tracked for commercial potential.
3. *New Technologies and Innovations*—This metric tracks those specific new technologies and innovations resulting from the Enterprises' programs that may have commercial application. While the above metric looks at overall potential, this metric focuses on whether that potential is indeed becoming a reality. It is critical that these technologies are identified in a timely fashion so the NCTN can assist the Enterprises in achieving maximum leveraging of these innovations.
4. *Partnerships*—This metric tracks each Enterprise's investment in partnership activities. Per the National Performance Review, the Agenda for Change, and the Government Performance Review Act, NASA is committed to investing 10 to 20 percent of its annual research and development base in partnership activities.
5. *Success Stories*—This metric tracks those NASA technologies that have had commercial impact. To be a success requires an acknowledged use of the technology.

10.5 Small Business Innovative Research and Small Business Technology Transfer Models

The SBIR and Small Business Technology Transfer (STTR) programs, from this point on identified as "SBIR/STTR," are foundational models for the strategic development and implementation of technology transfer and commercialization in support of the overall NASA commercial technology process.

Program Description

NASA invites eligible small business concerns to submit proposals annually for the SBIR/STTR programs. Through the solicited proposals, NASA seeks innovative concepts addressing mission program or focused technology needs described in the solicitation subtopics, but also offering high commercial application potential.

The structure of the SBIR program reflects a three-phase process to the innovation, development, and transfer of new products to the marketplace. These programs therefore have three phases: Phase I, the opportunity to establish the feasibility and technical merit of a proposed innovation; Phase II, the major research and development effort of the most promising Phase I projects; and Phase III, the development of a product or service to make it commercially available. Phase I and Phase II use SBIR/STTR funds, with all Phase III follow-on activities being capitalized by non-SBIR sources of funding with the pursuit of private-sector or Government sales.

SBIR/STTR Process Flow

Figure 10.5-1 illustrates the SBIR/STTR process flow. In addition, the SBIR/STTR handbook (<http://sbir.gsfc.nasa.gov/SBIR.html>) provides additional guidance. Beginning with NASA's strategic planning process in the upper left corner of Figure 10.5-1, the Enterprises are able to target appropriate technology areas for topic and subtopic development for submission to the SBIR/STTR programs. Each Enterprise provides developmental support and recommendation for the technical topics and subtopics included in the solicitations. SBIR/STTR proposals must suggest possible solutions to Enterprise mission program challenges or innovative concepts that meet a NASA mission need developed during strategic planning cycles and that have the potential for commercial application.

Solicitation respondents are expected to thoroughly explain their innovative concepts and how they plan to pursue commercial applications of their SBIR products or underlying technology. Proposals emphasize near-term applicability to NASA. While final selection is made by the SBIR/STTR source selection official, selections are made from Center-ranked recommendation lists, and preference is given to eligible proposals for which innovations are judged to have significant potential for NASA Enterprise programs and commercial applications.

NASA's Office of Aero-Space Technology provides, through the SBIR/STTR program executive director, the overall policy direction for the SBIR/STTR programs, while the NASA Goddard Space Flight Center serves as host for the Program Management Office. NASA Field Installations

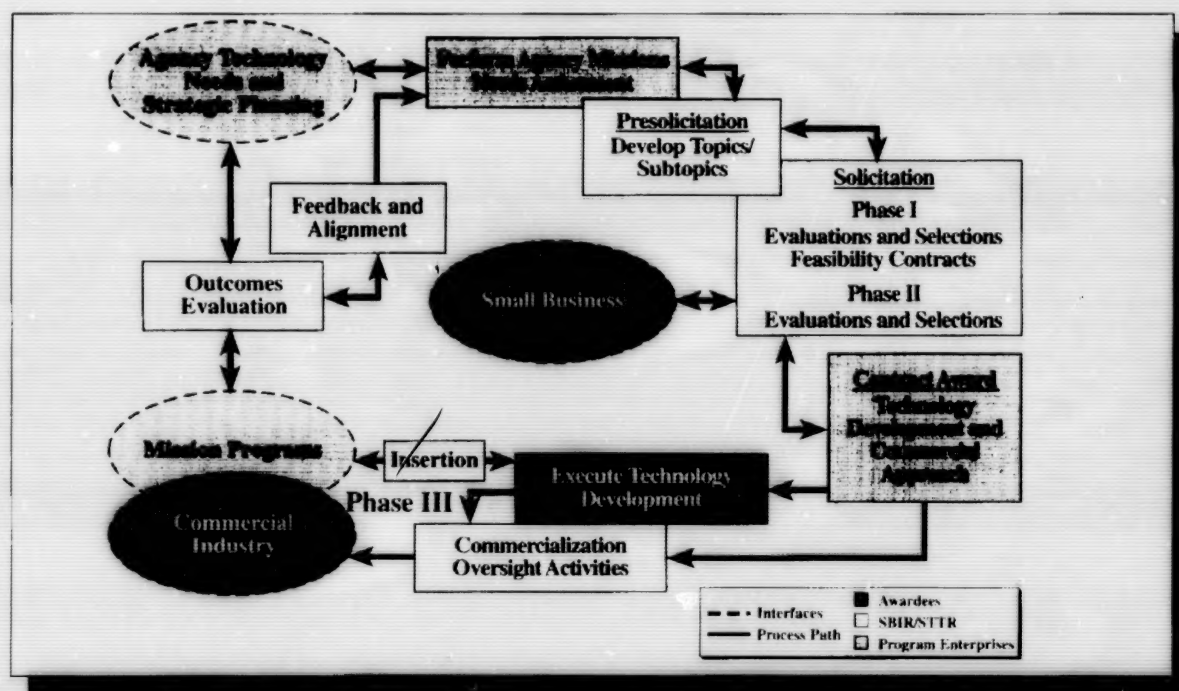


FIGURE 10.5-1. SBIR/STTR TECHNOLOGY DEVELOPMENTS COMMERCIALIZATION PROCESS FLOW

identify research and development needs, evaluate proposals, make recommendations for selections, and manage the individual projects.

SBIR/STTR contractors must have the capability to independently conduct the research and development they propose. During Phase I, contractors will have no more than 6 months in which to complete their Phase I projects and to submit their Phase I final reports and Phase II proposals.

In Phase II, contractors continue the development of those innovations shown to be feasible in Phase I and demonstrate a continued potential value to NASA and to the U.S. economy. Participation is limited to those contractors who have completed NASA SBIR/STTR Phase I projects. New fixed-price contracts are employed in Phase II with performance periods up to 2 years. The Government is not obligated to fund any specific Phase II proposal. The NASA SBIR/STTR programs fund about 40 percent of the Phase I projects in Phase II.

Phase III involves non-SBIR/STTR capital to develop commercial applications of a project, either from an additional NASA contract via other Federal agencies or through agreements in the private sector. Phase II and Phase III of the SBIR/STTR programs provide the opportunity for NASA Enterprises to integrate technologies or products under development within the SBIR/STTR programs with Agency mainstream research and development missions and programs.



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Appendices

Appendix A	Acronyms
Appendix B	Technology Readiness Levels
Appendix C	NASA Roadmaps
Appendix D	Web Access to NASA Technology Information

Appendix A

Acronyms

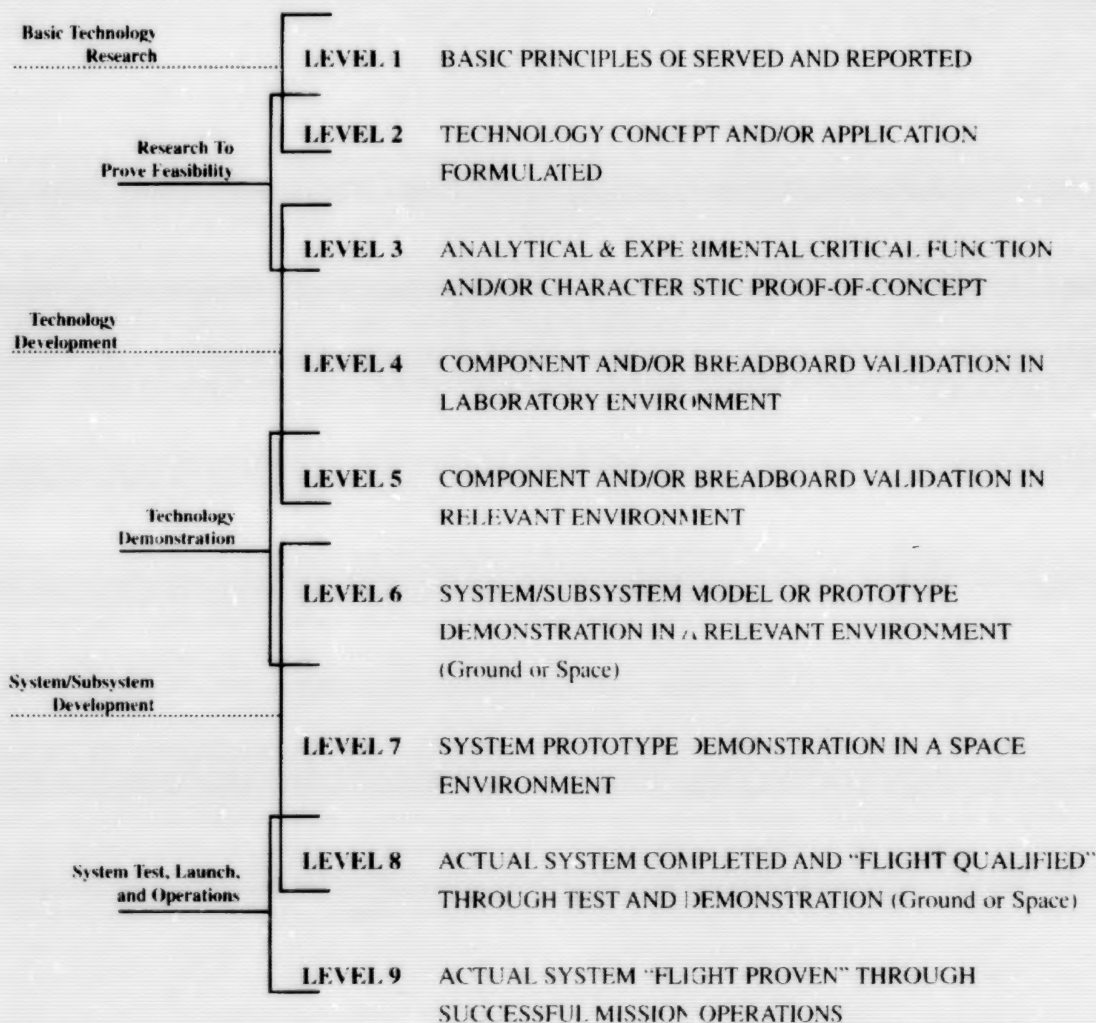
AACB	Aeronautics and Astronautics Coordination Board
AC	alternating current
ACTIVE	Advanced Controls Technology for Integrated Vehicles Experiment
ACTS	Advanced Communications Technology Satellite
AGATE	Advanced General Aviation Transport Experiments
AIAA	American Institute of Aeronautics and Astronautics
AST	Advanced Subsonic Technology (program)
ASTAR	Advanced Subsonics Transport Aircraft Research
ASTP	Advanced Space Transportation Program
AU	Astronomical Unit
BMDO	Ballistic Missile Defense Office
CCD	charged coupled device
CCTDP	Crosscutting Technology Development Program
CLCS	Checkout and Launch Control System
CRV	Crew Return Vehicle
CSC	Commercial Space Center
DARPA	Defense Advanced Research Projects Agency
DC	direct current
DEAR	Design for Efficient and Affordable Rotorcraft
DNA	deoxyribonucleic acid
DOD	Department of Defense
ELV	Expendable Launch Vehicle
EOCAP	Earth Observations Commercial Applications Program
EOS	Earth Observing System
ER&T	Engineering and Research Technology (program)
ERAST	Environmental Research and Sensor Technology
ESA	European Space Agency
ESE	Earth Science Enterprise
EVA	extravehicular activity
FAA	Federal Aviation Administration
FRIAR	Fast Response Industry Assistance for Rotorcraft
FY	fiscal year
GAP	General Aviation Propulsion (project)
GPS	Global Positioning System
HECC	High End Computing and Computation

HEDS	Human Exploration and Development of Space
HPCC	High Performance Computing and Communications
HSCT	High Speed Civil Transport
HSR	High Speed Research
ICAO	International Civil Aviation Organization
IIP	Instrument Incubator Program
INS	Inertial Navigation System
IR	infrared
ISCP	in situ consumable production
ISE	intelligent synthesis environment
ISRU	in situ resource utilization
ISS	International Space Station
KDD	knowledge discovery and data mining
LIDAR	Light Intersection Detection and Ranging
LIGA	Lithographic Galvanoformung Abformung
LTMCC	Large Throat Main Combustion Chamber
LWIR	long wavelength infrared
MEDS	Multifunction Electronic Display System
MEMS	Micro Electro Mechanical Systems
MMIC	monolithic microwave integrated circuits
MOVPE	metal-organic vapor phase epitaxy
MWIR	medium wavelength infrared
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection and Measurement
NCTMT	NASA Commercial Technology Management Team
NCTN	NASA Commercial Technology Network
NGI	Next Generation Internet
NIAC	NASA Institute for Advanced Concepts
NPD	NASA Policy Directive
NPG	NASA Procedures and Guidelines
NRC	National Research Council
NREN	NASA Research and Education Network
NRO	National Reconnaissance Office
NRTC	National Rotorcraft Technology Center
NSF	National Science Foundation
NSTAR	NASA (Electric Propulsion) Solar Technology Application Readiness
NSTC	National Science and Technology Council
NTTC	National Technology Transfer Center
OCT	Office of the Chief Technologist
OSS	Office of Space Science

PDD	Presidential Decision Directive
P/K	Pluto-Kuiper
PSA	Personal Satellite Assistant
RAAA	Remote Agent Autonomy Architecture
R&D	research and development
RLV	Reusable Launch Vehicle
RPA	Remotely Piloted Airplane
R&T	research and technology
RTCC	Regional Technology Transfer Center
RTG	radioisotope thermoelectric generator
SAR	Synthetic Aperture Radar
SBIR	Small Business Innovative Research (program)
SEDSAT	Students for the Exploration and Development of Space Satellite
SEU	Structure & Evolution of the Universe
SITF	Satellite Industry Task Force
SLWT	Super Lightweight Tank
SOCTP	Space Operations and Communications Technology program
SOMO	Space Operations Management Office
S&PU	Safety and Performance Upgrades
SSE	Space Science Enterprise
SSME	Space Shuttle Main Engine
STS	Space Transportation System
STTR	Small Business Technology Transfer (program)
SWIR	short wavelength infrared
TAP	Technology Acceleration Program
TCAC	Technology and Commercialization Advisory Committee
TIP	Technology Investment Program
TLC	Technology Leadership Council
TRL	Technology Readiness Level
UAV	unpiloted airborne vehicles
UCLA	University of California at Los Angeles
UNEX	university explorer-class
UV	ultraviolet
VHF	very high frequency
V&V	validation and verification

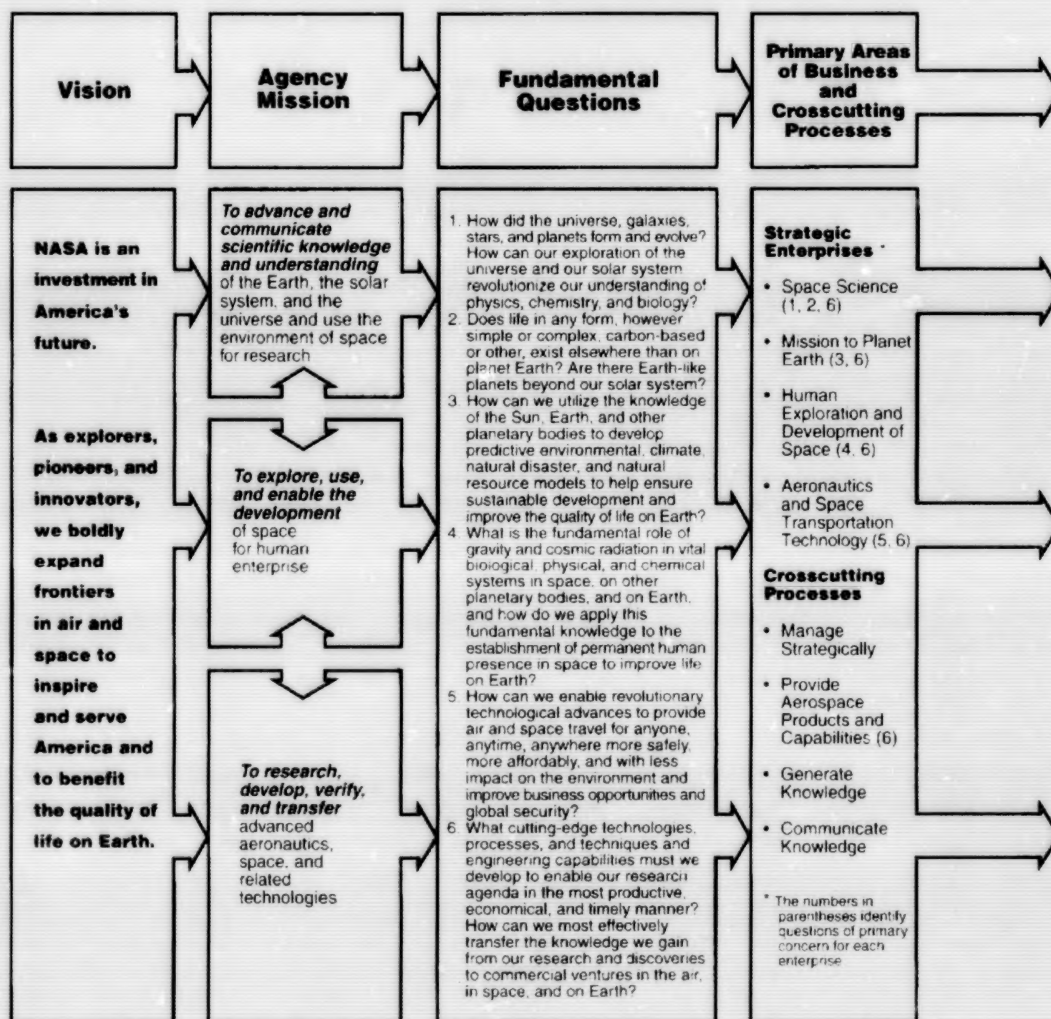
Appendix B Technology Readiness Levels

Within NASA strategy, nine Technology Readiness Levels (TRL) have been defined, ranging from the basic physical principles to a "flight-proven" system. The figure below provides these definitions. Typically, the goal is to take technology to a maturity level whereby it can be picked up and used in an Enterprise mission.

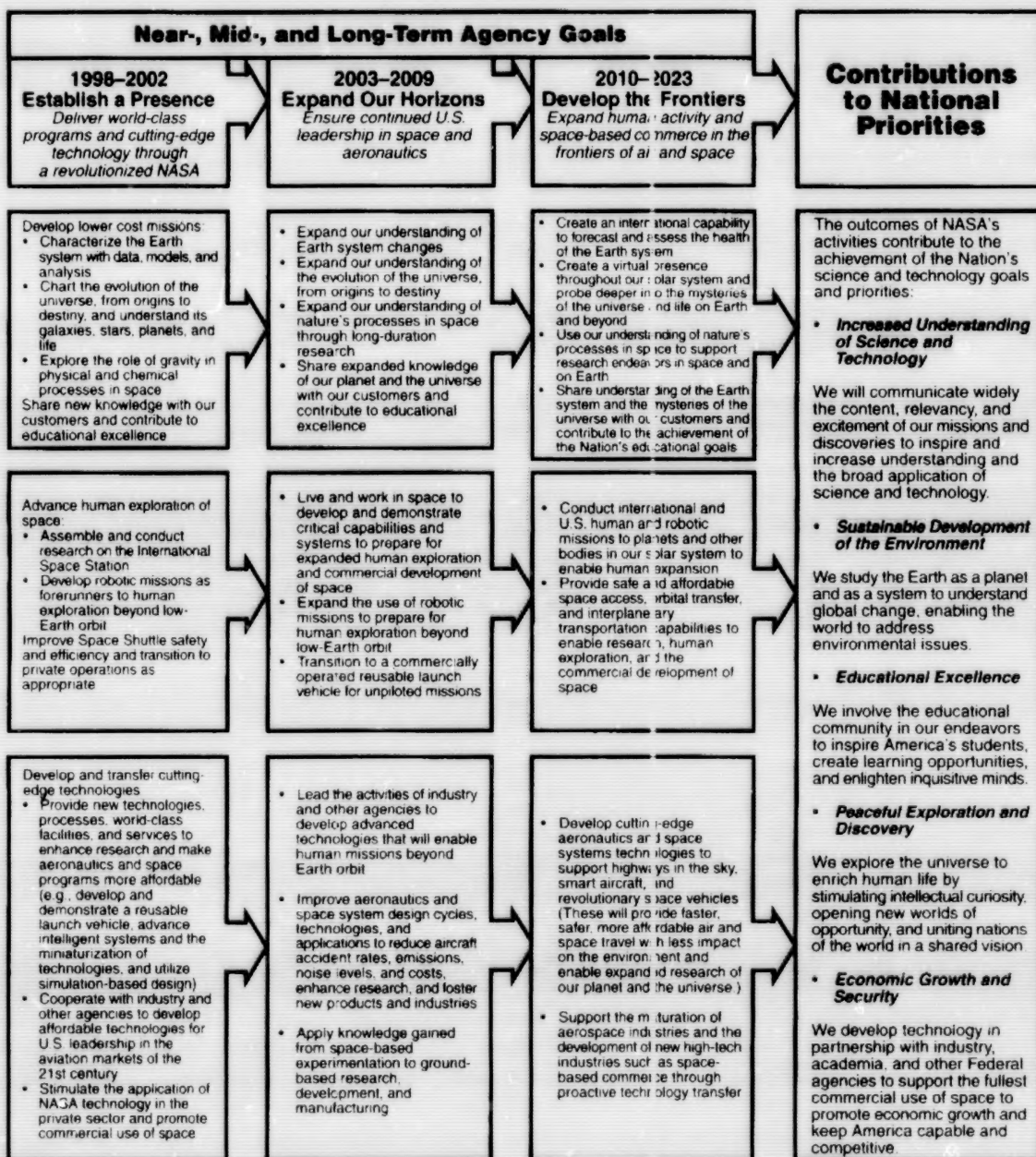


Appendix C NASA Roadmaps

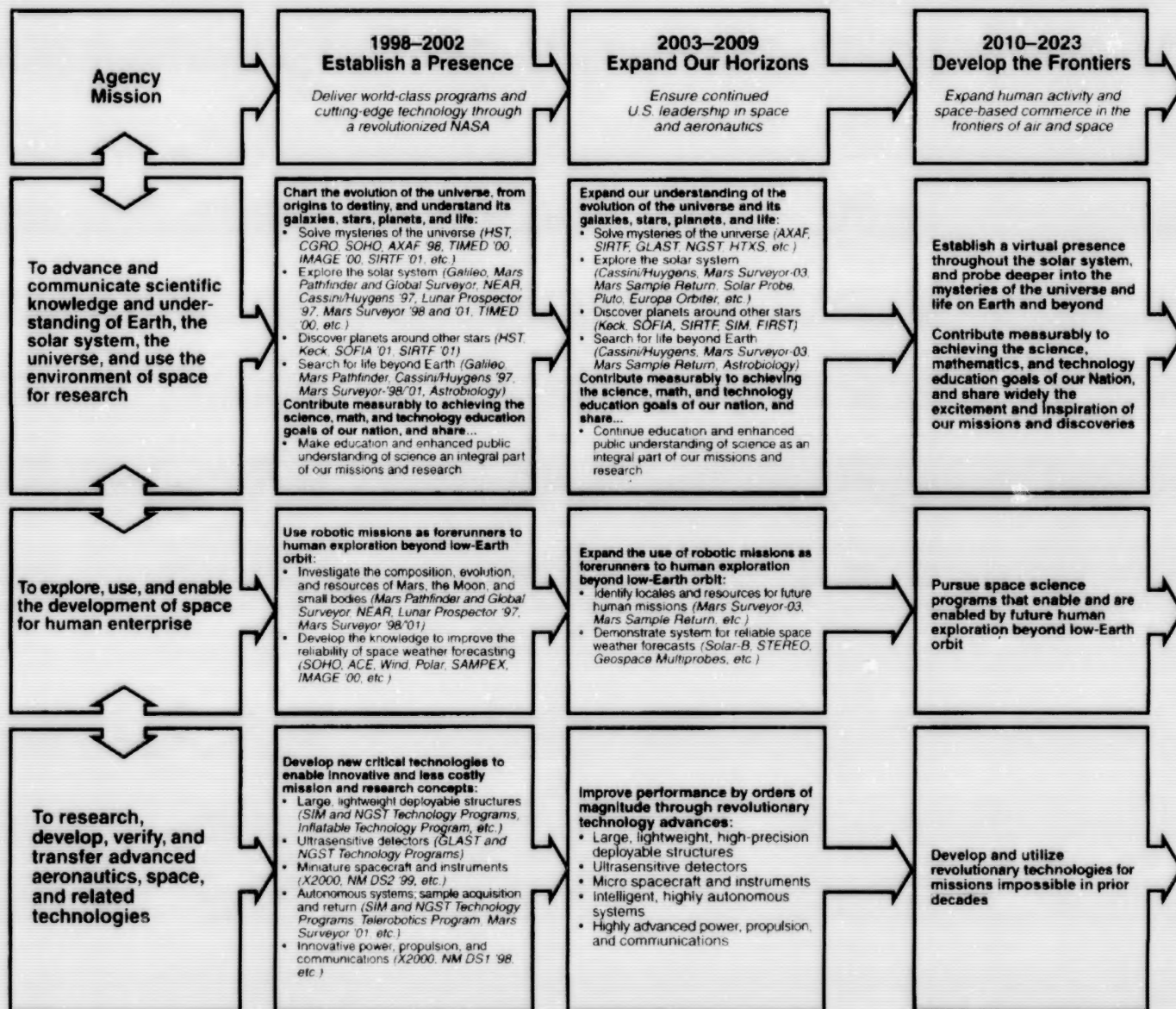
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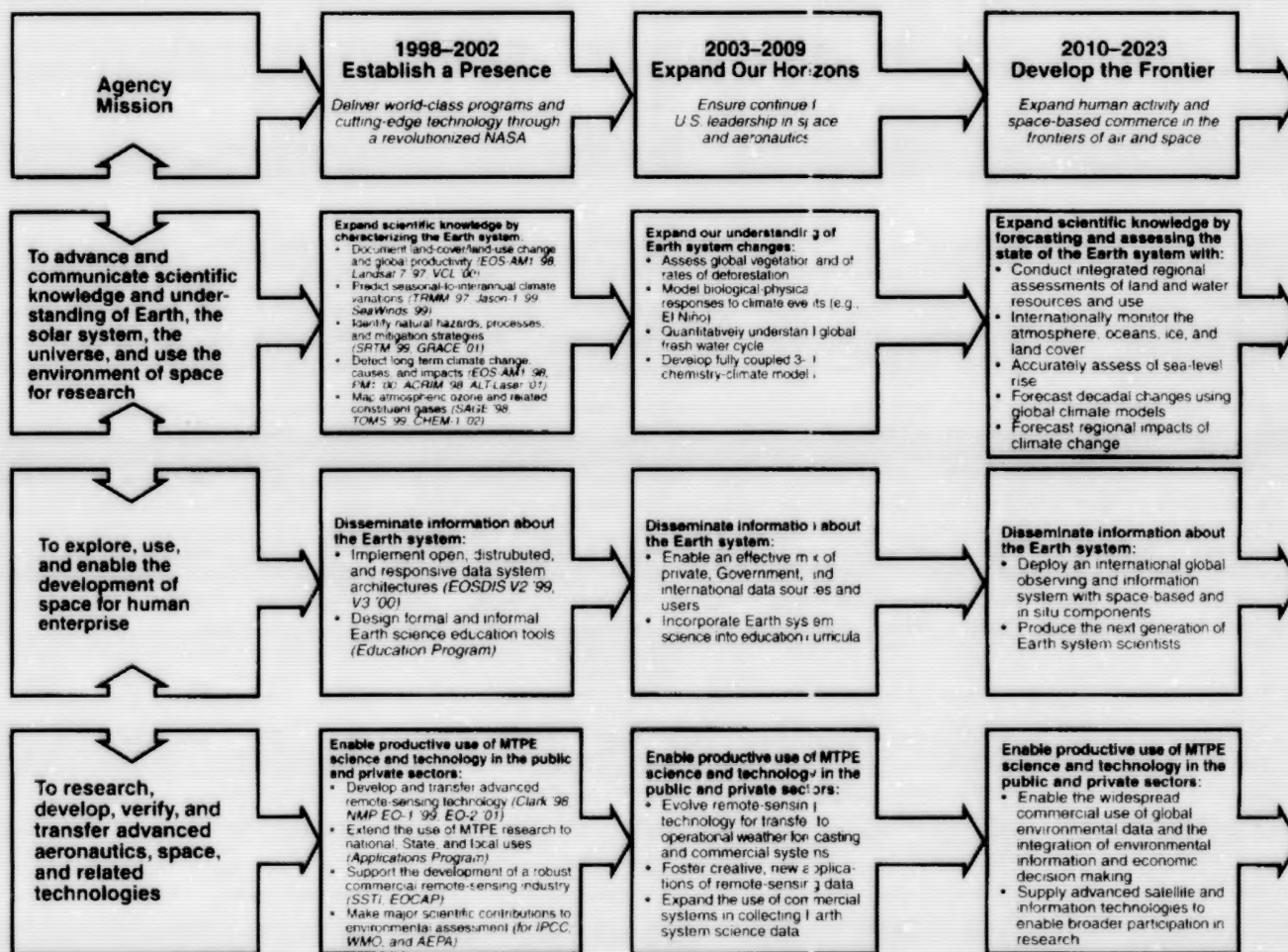
(b.) NASA ROADMAP PART 2



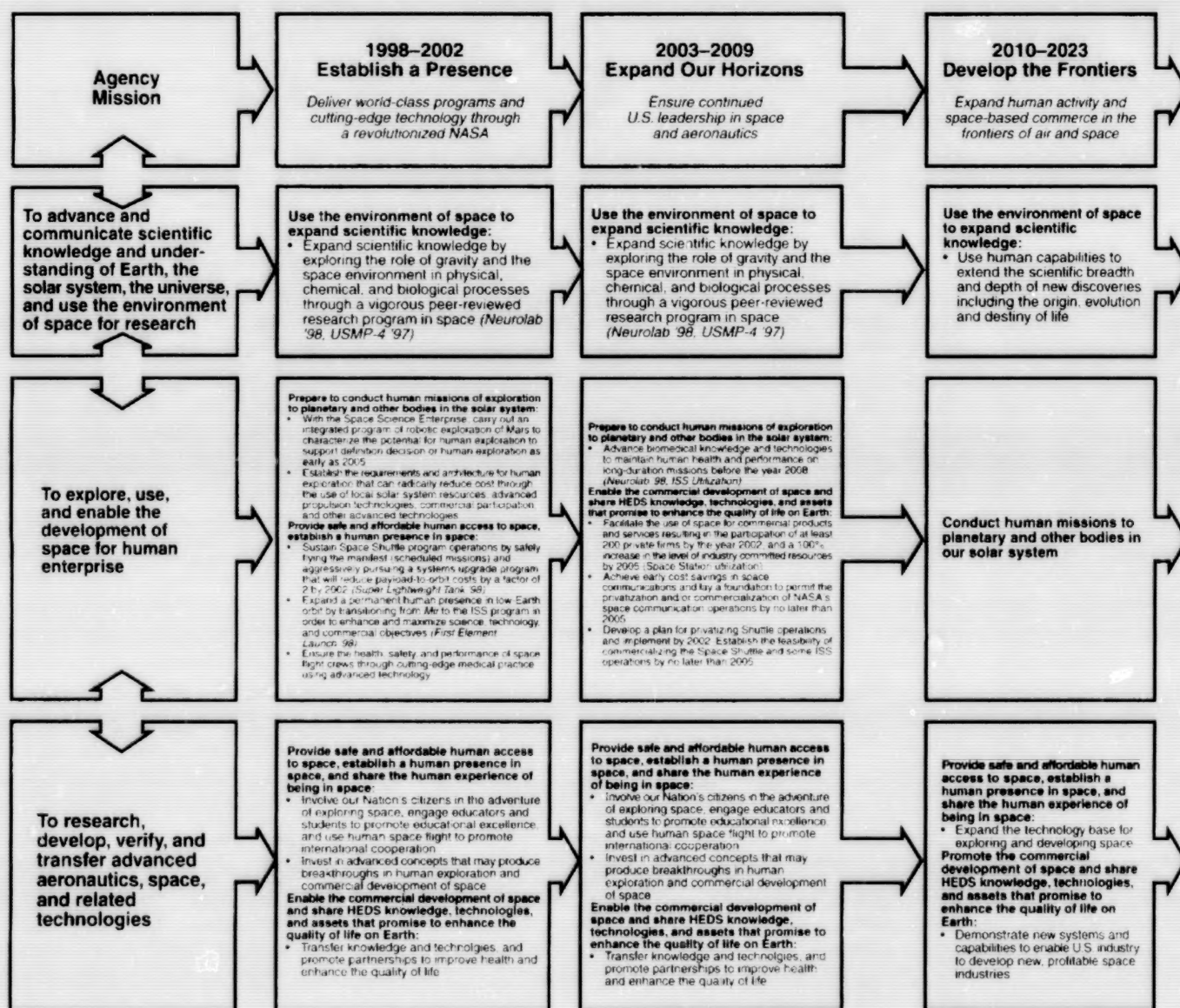
(c.) SPACE SCIENCE ENTERPRISE ROADMAP



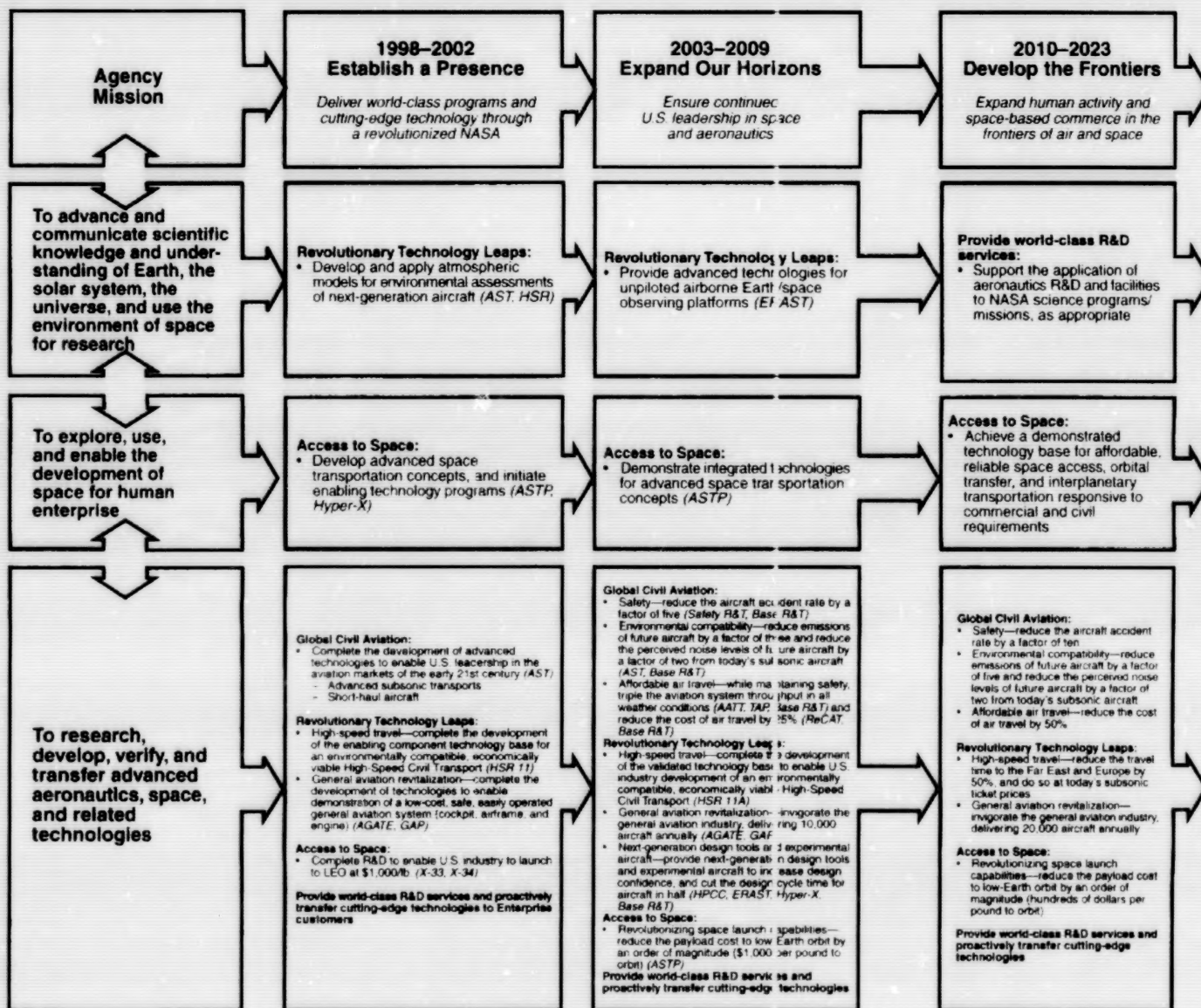
(d.) EARTH SCIENCE ENTERPRISE ROADMAP



(c.) HUMAN EXPLORATION AND DEVELOPMENT OF SPACE ENTERPRISE
ROADMAP



(f.) AERO-SPACE TECHNOLOGY ENTERPRISE ROAD MAP



Appendix D

Web Access to NASA Technology Information

Many of the documents and policy statements used to create the NASA Technology Plan are available through the Internet. Listed below are many of those sites:

National Space Policy (Fact Sheet)

<http://www.whitehouse.gov/WH/EOP/OSTP/NSTC/html/fs/fs-5.html>

NASA Strategic Plan

<http://www.hq.nasa.gov/office/nsp/>

NASA Strategic Management Handbook

<http://www.hq.nasa.gov/office/codez/strahand/frontpg.htm>

Office of Chief Technologist

<http://www.hq.nasa.gov/office/codea/codeaf/>

Office of Chief Engineer

<http://www.hq.nasa.gov/office/codea/codeae/>

NASA Enterprise Strategic Plans

Space Science

<http://www.hq.nasa.gov/office/oss/>

Earth Science

<http://www.hq.nasa.gov/office/MTPE>

Human Exploration and Development of Space

<http://www.hq.nasa.gov/osf/heds/>

<http://www.hq.nasa.gov/osf/>

<http://www.hq.nasa.gov/office/olmsa/>

Aero-Space Technology

<http://www.hq.nasa.gov/office/aerol>

NASA Commercialization Technology Network

<http://www.nctn.hq.nasa.gov/>

NASA Institute for Advanced Concepts (NIAC)

<http://www.niac.usra.edu>

National Research Council

<http://www.nas.edu/nrc/>

NASA Technology Plan

<http://actua-www.larc.nasa.gov/techplan/>

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